GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-20-G03 (R6144-0A0) GTRC/~~XXX~~ DATE 8 / 28/ 86

Project Director: Peter Parsonson School/~~XXX~~ CE

Sponsor: Georgia Department of Transportation

Type Agreement: Task Order No. 6 under BOA No. 90 dated 11/9/84

Award Period: From 6/23/86 To 5/23/88 (Performance) 8/23/87 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$ 71,730	$ 71,730
Funded:	$ 71,730	$ 71,730

Cost Sharing Amount: $ None Cost Sharing No: N/A

Title: Criteria for Two-Way Left-Turn Lanes Versus Other Median Treatments.

ADMINISTRATIVE DATA OCA Contact Brian J. Lindberg X-4820

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Defense Priority Rating: N/A

Military Security Classification: N/A
(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with Sponsor

COMMENTS:

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Accounting	Research Communications (2)	Other A. Jones

GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 11/23/88

Project No. E-20-G03/R6144-0A0 School/~~Lab~~ CE

Agreement dtd. 11/9/84

Includes Subproject No.(s) N/A

Project Director(s) P.S. Parsonson GTRC/~~GIT~~

Sponsor Georgia Department of Transportation

Title Criteria for Two-Way Left-Turn Lanes Versus Other Median Treatments.

Effective Completion Date: 5/23/88 (Performance) 5/23/88 (Reports)

Grant/Contract Closeout Actions Remaining:

- [XX] None
- [ ] Final Invoice or Copy of Last Invoice Serving as Final (Already Submitte
- [ ] Release and Assignment
- [ ] Final Report of Inventions and/or Subcontract: Patent and Subcontract Questionnaire sent to Project Director [ ]
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ____________

Continues Project No. ____________ Continued by Project No. ____________

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E-20-G03

Contract Research

GDOT Research Project No. 8602

Interim Report

CRITERIA FOR TWO-WAY LEFT-TURN LANES VS. OTHER MEDIANS

by

Peter S. Parsonson, Professor
Joaquin E. Vargas, Graduate Research Assistant
Marwan B. Abboud, Graduate Research Assistant

School of Civil Engineering
Georgia Institute of Technology

Contract with

Department of Transportation
State of Georgia

In cooperation with

U. S. Department of Transportation
Federal Highway Administration

October, 1987

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF CIVIL ENGINEERING
ATLANTA, GEORGIA 30332

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October 13, 1987

Mr. Tom Stapler
State Materials & Research Engineer
Office of Materials and Research
Georgia DOT
15 Kennedy Drive
Forest Park, GA 30050

Attention: Mr. Lamar Caylor, Research & Development Bureau

Dear Mr. Stapler:

Criteria for Two-Way Left-Turn Lanes Vs. Other Medians
GDOT Research Project No. 8602
Georgia Tech Research Project No. E-20-G03

The purpose of this project is to develop a set of design criteria for the choice between two-way left-turn lanes and raised-curb medians, considering both capacity and safety.

Transmitted herewith are three copies of an Interim Report. It supersedes and replaces the draft Final Report transmitted on June 17 of this year. That report showed that additional work was needed to complete the project satisfactorily and to substantiate all findings. Therefore we requested, and the Department approved, a no-cost time extension of the project to May 23, 1988. Also, the draft Final Report contained errors and omissions. This report corrects all of these, we hope.

Following is a list of the corrections that have been made, for your convenience in reviewing the differences between the two documents:

o The Acknowledgment expresses our appreciation to Mr. James Fincher of Traffic & Safety for his comments.

o The Table of Contents, which was somehow omitted in the printing of the earlier report, has been restored.

o The Abstract has been updated to show that, overall, the difference in the two designs in delay to turning vehicles was found to be insignificant. The Abstract was also changed to reflect updated findings and conclusions regarding safety, itemized next. Wherever a table was changed, the text explaining the table was corrected accordingly.

o Table 3 was given a new title and was changed to show that the difference in number of driveways per mile between the two designs is statistically significant.

o Tables 4 and 5 were clarifed in the meanings of certain headings. Also, the calculations of the overall averages of Accidents Per Mile Per Year and Accidents Per Million Vehicle Miles were corrected to weight each site properly; that is, the overall averages were recalculated using total accidents divided by total section miles (or total MVM). These corrections showed that the RM design, as compared to the TWLTL design, is lower by 20 percent in accidents per mile per year, and lower by 32 percent in accidents per million vehicle miles.

o Tables 6 and 7 were changed to show the correct overall averages for number of injury accidents, number of persons injured, and number of property-damage accidents. The tables show that the RM design is lower by 16 percent in injury accidents, 15 percent in persons injured, and 20 percent in property-damage accidents.

o Table 8 was corrected in the same fashion as those just described, to give overall averages for various types of collisions.

o Table 9, a summary of accidents per MVM and accidents per mile per year, was derived from the earlier Tables 4 and 5, which were corrected as just described. Table 9 was in turn changed to be compatible with them.

o The Abstract and Conclusions were changed to match these corrections.

o The Recommendations were deleted, as they have been superseded by the Department's specifications for the additional research to be performed in the remaining months of the project.

We are pleased to be a part of the interesting new work to be accomplished, and hope that the results will be useful to the Department.

Yours very truly,

Peter S. Parsonson
Professor and Project Director

ACKNOWLEDGMENTS

The authors are indebted to Tech graduates John L. Hibbard and Stephen P. Celniker, whose research results are referenced herein. Graduate student Larry Henson was most helpful in providing continuity over the course of the project.

GDOT engineers Doug Weems and Dick Graves promptly provided inventory and accident data, respectively. Lamar Caylor was the project monitor for the Department. The authors particularly appreciate the guidance provided by then State Road & Airport Design Engineer, Floyd Hardy, at the very start of the project.

The authors particularly appreciate the comments from GDOT engineer Jim Fincher, who reviewed an earlier submittal prepared by Tech graduate student Joaquin Vargas.

ABSTRACT

Sixteen arterial sections with two-way-left-turn-lane (TWLTL) medians, and seven with raised medians were identified in the Atlanta area as representing a wide range of ADT volumes and driveway densities. Left-turning traffic was observed during peak-volume periods and data recorded on left-turn stops, delay and amount of adequate-gap time for crossing opposing traffic. The data was analyzed to determine the capacity of a TWLTL design, and (along with accident data) to develop a set of design criteria for the design choice between the two types of medians.

Regarding delay, overall it was found that the difference in the two designs in delay for left-turning vehicles was insignificant. The highest delay observed was at two raised-median sites, not the TWLTL sites. It was found that the delay at both types of sites increased exponentially with ADT and was correlated with the product of hourly left-turning and opposing volumes. Regression analyses indicated that the TWLTL design results in less total delay when this product is less than 200,000 and there are fewer than 50 driveways per mile.

A computer simulation study was performed on one TWLTL section to determine the effect of changing it to a raised median. It was found that the delay at the signalized intersections was not much affected, provided U-turns were

prohibited there and the median had a mid-block opening. However, delay to left-turners increased sharply. It was concluded that raised medians need to be accompanied by service roads to connect the parking lots of contiguous businesses.

Accident data for mid-block and intersections combined was obtained for two years at 12 of the TWLTL sites and all seven of the raised-median locations. The raised-median design, as compared to the TWLTL choice, was found to be lower by 20 percent in accidents per mile per year, and lower by 32 percent in accidents per million vehicle miles (MVM). Injury accidents per MVM were reduced by 29 percent. All of these results were statistically significant at the 95 percent confidence level. Also, the raised-median design, as compared to the TWLTL choice, was found tobe lower by 16 percent in injury accidents, 15 percent in persons injured, and 20 percent in property-damage-only accidents, all of which were calculated on a "per mile" basis.

Multiple regression analyses found TWLTL accidents per mile per year to correlate well with peak-hour volume and the number of driveways per mile, while accidents at raised-median sections were modeled well by means of peak-hour volume and signals per mile. The raised-median design was found to be associated with fewer accidents than the TWLTL design only when there are two or fewer signalized intersections per mile, 80 or more driveways per mile, and a two-way peak-hour volume of less than 3000 vehicles.

More time will be required to substantiate all of the findings of this project to date.

KEY WORDS: TWLTL, two-way left-turn lane, traversable median, flush median, raised median, curbed median, arterial median, mid-block capacity, mid-block delay, arterial safety

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INTRODUCTION

The report begins with an orientation to the problem that prompted this project. The specific research objectives that were developed are then explained, followed by the benefits that are expected from the project. The potential for implementation of the project results by the Department are stated, and the approved plan of work set forth.

Orientation to Problem

First it is necessary to describe the current state of the art of median-type selection, focusing on the knowledge gaps that indicate the need for further research.

Two-way left-turn lanes (TWLTLs) have been used increasingly as the median of choice. By extending the principle of providing separate storage lanes for left-turn vehicles at intersections, TWLTLs are intended to shadow (provide refuge for) left-turning vehicles from through traffic. Many traffic engineers and highway designers have noticed that the business sector, politicians and the motoring public prefer the TWLTL operation to raised-median designs that restrict midblock left turns. The advantages of the TWLTL have been documented by Nemeth (1), Parker (2), Glennon (3) and others, as summarized herein in the review of literature (Appendix B) and the annotated bibliography (Appendix C). For the purposes of this introduction it is useful to summarize the recent, unpublished experience of the City of Los Angeles (4).

Los Angeles has hundreds of miles of major arterials with high driveway density and continuous strip commercial development. Their typical modern arterial has six through lanes, driveway access to all adjoining properties, a continuous painted TWLTL, and an ADT of approximately 40,000. The City uses the TWLTL as opposed to raised medians for the following reasons, according to one of the L.A. engineers:

- o Reduction in circuitous travel distance
- o Improved efficiency of intersections through reduction in intersection turning movements.
- o Improved operation of the traffic-signal system through elimination of <u>most</u> left-turn phasing.
- o Great increase in the operating efficiency of emergency vehicles.
- o Reduction in the cost of highway construction and maintenance.
- o Accommodation of traffic during construction, maintenance and emergency conditions.
- o Elimination of the median-island fixed object, which can be a hazardous obstruction (particularly when operating speed exceeds 45 mph).
- o Striping and geometrics can be revised at minimal cost and effort.
- o No increase in total accidents, as compared to raised-median operation, according to City statis-

tics gathered over the past 20 years.

If the City of Los Angeles is reasonably satisfied with TWLTL operation on its busy arterials, can there possibly be traffic conditions that demand more of a TWLTL than it can deliver? Is there a point at which traffic volumes, especially left turns, exceed the capacity of a TWLTL? At what loading does a TWLTL break down in operation, no longer providing the capacity and/or safety that could perhaps be obtained from an alternative median treatment?

The literature only hints at answers to these questions. In 1977 the Federal Highway Administration (5) pointed out in its Design of Urban Streets course notebook that he number of movements made in a TWLTL can become too large, with a resultant increase in accidents or near accidents." In the same year Nemeth reported that a questionnaire survey showed that some respondents said that "too many left turns" were a factor contributing to the ineffectiveness of the less-successful TWLTL projects.

When left-turn volumes are very high, a left-turning vehicle may not be able to enter the TWLTL as soon as desired. It may decelerate or even stop in the inside through lane, creating delay to through traffic and a loss of capacity and efficiency. Further, heavy volumes on multiple through lanes may prevent a left-turning vehicle from finding a safe, acceptable gap for an extended period of time. Left-turning vehicles may accumulate in the TWLTL to the point that through vehicles in the inside lane are stopped and delayed. A deterioration is safety, as well as capacity, is apparent under these conditions.

There is a notable absence of capacity data on TWLTLs in the literature. Parker (2) pointed out in 1979 that "In great need of attention is the problem of determining the capacity of alternative median treatments by means of factors other than mid-block delay." The standard references on arterial capacity say little on the subject, because capacity is considered to be limited by G/C ratios at signalized intersections.

In the absence of published research on these points, there are at present no warrants setting forth the upper limits of volumes, especially left-turn movements, for which the TWLTL is an appropriate median treatment. The TWLTL may be overapplied currently, that is, used in locations where it is not as good as an alternative median treatment.

Even in the absence of published material, the problem can be seen and appreciated on Georgia roads and streets. For example, Roswell Road in Sandy Springs frequently has severe congestion of mid-block left-turning volumes, requiring off-duty police to stop traffic to allow these movements. Memorial Drive in Decatur and Stone Mountain is a seven-lane TWLTL design where the danger to pedestrians and turning vehicles is obvious even to the layperson.

State Route 5 in Cobb County was allowed to develop independently on either side of the road. Crossroads are staggered, creating overlap of the left-turn movements. It is difficult to install left-turn signal phasing, and in general the left-turning vehicles find it difficult to compete with one another. Uncontrolled development adds to the dilemma of median selection.

The GDOT State Traffic and Safety Engineer, Mr. Archie C. Burnham, made a presentation on median selection to the Cobb County Board of Commissioners on April 28, 1987 (6). He showed in the table reproduced below the existing and projected accident statistics (per 100 million vehicle-miles of travel) for four facilities in the Atlanta area.

URBAN ARTERIAL ROADS

	LENGTH	TRAFFIC EXISTING	TRAFFIC FUTURE	DRIVEWAYS PER MILE	STREETS PER MILE	85TH PERCENTILE SPEED	EXISTING RATES ACC	EXISTING RATES INJ	EXISTING RATES FAT	PROJECTED RATES ACC	PROJECTED RATES INJ	PROJECTED RATES FAT
ATLANTA ROAD	5.60	16,000	34,000	31	5.0	46	652	240	2.03	500 (4LD)	200	1.50
										900 (5L)	300	3.00
SOUTH COBB DRIVE	4.12	31,000	40,000	16	4.1	51	725	294	3.22	1100 (5L)	350	3.40
TARA BOULEVARD	9.55	26,300	36,000	26	4.5	52	434	204	1.17	540 (4LD)	220	1.50
HOLCOMB BRIDGE ROAD	1.36	51,600	65,000	31	5.1	49	630	192	1.56	860 (6LD)	250	2.00

Atlanta Roadway is a two-lane in south Cobb County currently being considered by the Department for upgrading to a four-lane divided facility. South Cobb Drive currently has five lanes, including a TWLTL. Tara Boulevard is a four-lane divided highway (meaning that it has a raised median) in Clayton County. Holcomb Bridge Road, in Fulton County, is a six-lane divided route. The table shows that Department projections for Atlanta Roadway indicate that the rate of accidents with a four-lane divided facility will be 500, compared to 900 for an upgrade to a five-lane design (with TWLTL).

Mr. Burnham went on to review the Virginia research by Martin Parker (2), and concluded that the GDOT agrees with his findings and leans toward preferring a raised median section when a) volumes exceed 20,000 per day, b) there are more than 25 driveways per mile, and c) it is feasible to provide sufficient capacity for U turns at the intersections.

He also explained that the Department has performed studies showing that divided facilities hold a substantial edge over TWLTLs in safety performance. They have found accident experience to be related to the number of driveways per mile, the treatment of public streets, pedestrians, sight distance, speed and intersectional capacity. However, the Department has not yet finalized a specific guideline, presumably because further data is needed from additional research such as this present project.

In summary, there has been an unfilled need for research that would provide quantitative (not merely qualitative) guidelines for choice of median treatment. The scope of the research should include not only accident frequency and severity but also volume/capacity considerations. The research should provide a clear answer to the question of what level of traffic volumes, especially turning volumes, is the maximum for both safe and efficient operation of TWLTLs.

Research Objectives

The GDOT has set forth the project objectives as follows:

(1) That a set of design criteria be developed for the use of two-way left-turn lanes (TWLTLs) and raised-curb medians; and

(2) To include a capacity analysis of TWLTLs.

The scope of the research should include not only accident frequency and severity but also volume/capacity considerations. The research should provide a clear answer to the question of what level of traffic volumes, especially turning volumes, is the maximum for both safe and efficient operation of TWLTLs.

Expected Benefits from the Project

The significance of the project is its potential to produce quantitative guidelines--numerical criteria--to assist the designer in choosing, in a systematic way, the proper median treatment for a project. The benefits to be expected from this research are a rational, logical and defensible selection of median treatment that will provide a proper balance between roadway capacity and access to abutting property.

Potential Implementation by the Department

The GDOT is actively engaged in widening two- and three-lane highways to cross-sections that need to be divided using some type of median for purposes of capacity and safety. An example is SR 5 in Cobb County, which is soon to be widened from three lanes to a five-lane section with a TWLTL. The Department is in need of firm data that would help to convince local interests of the proper choice of median type.

Another example is Memorial Drive from I-285 eastward to Stone Mountain. This is a seven-lane section with a TWLTL. There have been 13 fatalities on that four-mile stretch since 1978, and 45 percent of the 800 accidents in 1986 happened in midblock. Therefore the GDOT is proposing to replace the TWLTL with a concrete barrier or a raised median 10-feet wide, with seven U-turn crossings.

If the results of the proposed research had been available in time for these decisions, they would have been used to provide a systematic basis for the median selection.

Work Plan

The approved work plan for the project is included herein as Appendix A. The project began in July, 1986 and finished in June, 1987. The next section of this report provides an overview of the various procedures that were carried out in implementing the work plan.

PROCEDURE

This section of the report explains the steps that were carried out in fulfillment of the approved work plan, which is detailed herein as Appendix A. First there is given a chronology of project phases and personnel, to assist the reader in understanding the various documents that have been produced by the project. The next headings are taken directly from the list of tasks set forth by the work plan.

Chronology of Project Phases and Personnel

It is helpful to begin with a narrative of the way in which the project has been pursued since its beginning in July, 1986.

o During that summer a review of literature and an annotated bibliography were produced; they were submitted to the GDOT by letter of October 26, 1986.

o In that same summer graduate research assistant John L. Hibbard collected extensive data at a TWLTL location on Roswell Road in Sandy Springs, and at a raised-median location on Holcomb Bridge Road one and one-half miles west of Georgia Highway 400. These became the pilot locations for the project Phase I, Design of Methods of Evaluation. Hibbard developed a method for selecting sites, and detailed procedures for data collection. He also developed and tested computerized methods to analyze the gathered data. His findings are summarized later herein.

Hibbard's report (7) was transmitted to the Georgia DOT by letter of October 16, 1986. Hibbard's data-collection procedures are included herein as Appendix D.

o During the summer of 1986 another graduate student, Stephen P. Celniker, studied the effect of median type on delay at signalized intersections. He recorded field data on Roswell Road in Sandy Springs, which is a TWLTL location, and estimated the delay at Hilderbrand Road and Sandy Springs Place if the design had been a raised median instead. Like Hibbard's study, Celniker's work resulted in a detailed Masters report (8) that was transmitted to the GDOT by letter of October 16, 1986. Celniker's findings are summarized later in this report.

o Later that summer graduate students Lawrence Henson and John Hibbard obtained extensive inventory data from Mr. Doug Weems of the Planning Data Services Bureau located in Chamblee. They made use of the Coding and Procedures Manual to begin to determine 10 TWLTL and six raised-median candidate sites based on two criteria: ADT and level of roadside development (measured in driveways/mile).

o In September of 1986 a new graduate research assistant, Joaquin Vargas, began work on the project. With Henson providing continuity from the work of the summer, the two of them drove to many candidate sites. A few were obvious choices, so Vargas hired observers and began field-data collection in October. The GDOT sent review comments on the site list in November, and by early January we proposed a "final" group of 12 TWLTL sites and seven raised-median sites, an increase of three over the 16 we had proposed in the original Work Plan.

o In January, 1987 another new graduate student, Marwan Abboud, began work. He was oriented by Vargas and Henson and proceeded to perform the accident research for the project, using statistics provided by Mr. Dick Graves of the Traffic & Safety Division, for the 12 TWLTL sites and the seven raised-median sites. Much of his analytical work was based on the powerful BMDP statistical package run on the Georgia Tech CYBER mainframe computer.

o Statistical analysis of both the field-collected delay data and the accident data was performed during the winter and spring months. A large number of preliminary plots were generated by the Lotus 1-2-3 computer program. It appeared from these graphs that more sites were needed in order to increase the statistical reliability of the inferences drawn from the data. Vargas and his field crew went to four more TWLTL sites in April and May. He included these sites, for a total of 23, in his delay analysis.

o Like Hibbard and Celniker, Vargas prepared a Masters report to be sent to the GDOT as a supplemental product. It was transmitted to the Department by letter of June 7, 1987. This report went well beyond the Work Plan by applying the microscopic computer simulation program NETSIM to investigate the capacity of a TWLTL. Vargas simulated a section of Memorial Drive in Stone Mountain using this program. He increased the through volumes on this 7-lane arterial, holding the percent of left-turn traffic constant at its observed existing level, to attempt to determine at what volume there would be a breakdown in operation. Vargas also assisted Abboud in the analysis of the accident data, and provided some tentative findings and conclusions in his report.

o The last phase in the procedure has been the preparation of this final report. It includes all of Abboud's interpretation of the accident analysis. (There is no separate Masters report by Abboud, as he is a Ph.D. candidate and has not yet chosen a dissertation topic).

Review of Literature

A thorough review of the literature is included herein as Appendix B. That material groups the literature as follows: 1) Accident research, 2) Operational characteristics, 3) Volume/capacity research, 4) Computer simulation, 5) Comparison of TWLTLs with other median treatments, and 6) Other relevant literature.

Accident-research projects have usually focused on one of two basic methodologies: comparison of accident rates before and after the installation of a TWLTL, or determination of TWLTL effectiveness based on benefit-cost ratios.

Glennon (3) determined in the mid-1970's that the TWLTL is slightly inferior to the raised median where frequent driveways (more than 60 per mile) are in combination with "high" arterial street volumes (more than 15,000). His estimates found it to be a more-effective accident-reduction technique when the roadside is developed to less than 30 driveways per mile and ADT is less than 5,000.

Parker(2) in Virginia developed a set of regression equations requiring four input variables: ADT, numbers of cross-streets and signal per mile, local population, and driveways per mile. His conclusion was that a TWLTL is safer when the number of streets per mile is low (say, 5), regardless of the number of signals per mile, ADT and city population. However, when the number of streets per mile increases to 15, a raised median is preferred, regardless of the number of signals or driveways, or traffic volumes. Because raised curbs are fixed objects, Parker stated that raised medians should not be used when operating speeds exceed 45 mph.

The most-recent accident research was reported by Harwood in 1986 (10). Unfortunately, the groupings for ADT extended only up to 20,000, with one category for ADTs over 20,000 to cover high-volume arterials. A pervasive problem in accident research has been inadequate consideration of major arterials with ADTs of 30,000 to 70,000.

Benefit-cost-ratio research by Harwood and Glennon (11), and also by Thakkar (12), has uniformly shown that a TWLTL is preferred, even for high levels of ADT and roadside development. This is because of the low initial construction cost.

Regarding operational characteristics, Nemeth (1) found that in two out of three cases the installation of TWLTLs increased running speeds.

The concept of a "capacity" of a mid-block section with a TWLTL is not covered well in the literature. The current edition of the Highway Capacity Manual (13) provides no assistance. Fisher (4) observed TWLTL operation to be "satisfactory at best" on seven-lane facilities with ADT of 40,000 in Los Angeles. Lebel (14) stated that a five-lane section near Grand Rapids, Michigan is not operating as well at 40,000 ADT as it did at lower volumes. The State of Washington (15) has an upper limit of 25,000 ADT for their TWLTL designs. Thompson (16) echoed that upper limit for a five-lane design, and stated that 40,000 exceeds the practical capacity of a seven-lane road.

The Georgia Division of the Southern Section, ITE, performed a literature search cited by Nemeth (1). The Georgia group recommended that the TWLTL design be used on five-lane roads with ADTs in the range of 10,000 to 25,000. They concluded that the benefits of a TWLTL become questionable as volumes approach capacity, due to the lack of gaps (in opposing traffic) needed to make left turns.

Sawhill and Hall (17), also, stated that a basis for deciding whether to install a TWLTL would be the observation of time gaps of sufficient length for left-turn movements to be accomplished.

Although there are several computer-simulation models (18, 19, 20) that could potentially be used to help determine the capacity of a TWLTL, none has produced results of any significance. McCoy (20) designed his program TWLTL-SIM to abort left turns when those turning movements cause jammed flow. When such a jam is encountered we could speculate that probably most motorists will decide to drive on to the next free-flow location and make a U-turn. There seems to be no provision in McCoy's model for this.

Some of the literature focuses on comparisons of TWLTLs with raised or depressed medians. Most of this material is in the form of design guidelines. The current AASHTO "Green Book" (21) states that any form of access control should limit the number of conflict points, separate basic conflict areas, reduce maximum deceleration requirements, and remove turning vehicles from through lanes. The Federal Highway Administration (5) recommends TWLTLs for their capacity to store left-turning vehicles safely. They mention that very high concentrations of vehicles at raised-median openings could contribute to degradation of flow.

Development of Method to Examine Roads

We met with Mr. Doug Weems of the Planning Data Services

Bureau, GDOT, located in the Chamblee office. He provided inventory data for our use in determining the locations of roads with median treatments including TWLTL (actually coded as an auxiliary lane, not a median) and raised-curb medians. He provided the 1985 edition of the Systems Inventory Coding and Procedures Manual. In accordance with the Work Plan, we limited our scope to sites close enough to Atlanta to be visited without overnight travel.

Attempts to use photologs to determine road alignment, major intersection spacing, and the level and type of roadside development proved to be less than completely satisfactory, partly because the photologs were several years old. Therefore all candidate sites were visited by project personnel.

<u>Selection of Field Data-Collection Sites</u>

In accordance with the Work Plan, it was attempted to find the following sites: 10 TWLTL sites (total) falling into three ADT categories: less than 18,000, between 18,000 and 30,000, and greater than 30,000. Also 6 raised-median sites falling into two ADT categories: less than 30,000 and greater than 30,000. For each volume category, sites were sought with driveway densities in three ranges: less than 50/mile, between 50 and 100/mile, and greater than 100/mile.

By letter of October 16, 1986 we proposed 10 TWLTL and six raised-median locations as candidate sites for data collection. After receiving comments from the Department on November 4 we made appropriate changes and submitted a final list on January 9, 1987 showing 12 TWLTL and seven raised-median sites. That was the grouping used by Abboud for his analysis of accidents. Vargas, also, did his delay research on these 19 sites, but decided in May of 1987 to add four TWLTL sites in order to enlarge the data base of sites with high ADT (over 30,000) and driveway densities in the range of 50 to 100 per mile. That made a total of 23 sites for his delay work. Of the 23 sites listed next, the four that were added are indicated by an asterisk.

__Raised-Median Sites__

ADT	Driveways	Location
Less than 30,000	Less than 50/mi	SR 42, Moreland Ave., from South River Bridge (which is 0.2 mi south of South River Indus. Blvd to a point 0.2 mi south, ADT 26,904, drives 20/mi (Site 1R)
	50-100/mi	Forest Parkway from Old Dixie Rd to Hale Rd, ADT 25,096, drives 62/mi (Site 2R)
	More than 100/mi	No sites
More than 30,000	Less than 50/m	Buford Highway from I-285 north 0.2 mi (Krystal/Eye-Rite), ADT 51,409, drives 35/mi (Site 3R)
		Tara Blvd from Morrow Indus Blvd south 0.5 mi (second gap), ADT 50,703, drives 46/mi (Site 4R)
	50-100/mi	Ga 85 from Roundtree Rd to Ga 138, ADT 36,233, drives 91/mi (Site 5R)

		Holcomb Bridge Rd from Graimes Bridge Rd to Old Roswell Rd (Pilot Section), ADT 47,972, drives 70/mi (Site 6R)
	More than 100/mi	SR 70, Fulton Industrial Blvd from Wendell Dr to Martin Luther King, Jr. Dr, ADT 35,883, drives 105/mi, (Site 7R)

<u>**TWLTL Sites**</u>

ADT	**Driveways**	**Location**
Less than 18,000	Less than 50/mi	No sites
	50-100/mi	SR 124 in Lawrenceville, from Gwinnett Dr north 0.2 miles, ADT 13,854, drives 75/mi (Site 1T)
		SR 20 in Lawrenceville, from Phillips R to Appleton Rd, ADT 15,487, 87 drives/mi (Site 2T)
	More than 100/mi	No sites
18,000 to 30,000	Less than 50/mi	Memorial Drive (US 78, SR 10) east of Hairston Rd, from Englewood Dr to a point 0.2 mi east, where a raised median starts, ADT 28,300, drives 35/mi (Site 3T)
	50-100/mi	US 78 in Snellville, from Cindy Lane east 0.2 mi, ADT 22,380, drives 60/mi (Site 4T)
	More than 100/mi	Candler Road from Misty Waters to Eastwyck Rd, ADT 21,538, drives 105/mi (Site 5T)
More than 30,000	Less than 50/mi	No sites
	50-100/mi	Cobb Parkway from Spring Rd/Circle 75 Parkway north 0.2 mi, ADT 45,566, drives 65/mi (Site 6T)
	*	Cobb Parkway from 0.2 mi. south of Windy Hill Rd. to a point 0.2 mi

south, ADT 40,500, drives 60/mi (Site 16T)

Old National Highway from Old Bill Cook Rd to Jolly Rd, ADT 45,366, drives 80/mi (Site 7T)

Roswell Rd from Midvale Dr to Rickenbacker Dr, ADT 32,745, drives 65/mi (Site 8T)

* Buford Highway north of I-285 from 0.1 mi north of Longmire to a point 0.2 mi. north, ADT 51,400, drives 60/mi (Site 14T)

* Buford Highway from McClave Drive to a point 0.2 mi. north, ADT 38,700, drives 90/mi (Site 15T)

* Memorial Drive from 0.2 mi. east of I-285 to a point 0.2 mi. east, ADT 55,400, drives 55/mi (Site 13T)

More than 100/mi

Ga. 85 from Valley Hill south 0.2 mi.(to Del Taco/Taco Bell), ADT 36,233, drives 140/mi (Site 9T)

Jonesboro Rd from College St/Thurmond Rd south 0.2 mi., ADT 32,636, drives 100/mi (Site 10T)

Memorial Dr from entrance to DeKalb Community College northeast 0.27 mi, ADT 43,395, drives 107/mi (Site 11T)

Roswell Rd from Sandy Springs Pl to Hilderbrand Rd (Pilot Section), ADT 35,736, drives 115/mi (Site 12T)

Study sections for TWLTLs were selected to be 1000 feet long. That range did not include any signalized intersections, and unsignalized intersections with minor streets were avoided to the greatest extent possible. (Vehicles turning left into a minor road were not counted).

If the study section had a raised median, left-turning volumes were counted at a median gap which does not provide a direct left turn into a minor cross street.

Field-Data Collection

The details of the field-data-collection procedure were developed and described by Georgia Tech graduate student John Hibbard in his Masters Special Research Problem (7). Appendix D herein summarizes the field procedure and includes the five data-collection forms that were developed for this project.

Hibbard's procedures were developed at the two pilot sites (Roswell Road for the TWLTL site and Holcomb Bridge Road forthe raised-median location). His procedures were adopted by Vargas for the performance of the main project (following the pilot work). However, there were two differences in the field work performed by these two investigators, as follows.

Hibbard went to each of his two sites 15 times each, for about 20 minutes each time, at various times of day designed to ensure that the peak period was not missed. He observed both left turns simultaneously and logged them without differentiation as to direction.

Vargas went to each of his 23 sites two times each, for about 40 minutes each time, at the peak periods determined by studying volume counts and asking the local traffic engineer. One time of day typically was 1 pm and the other was 5 pm. Vargas observed one left-turning movement at 1 pm and the other at 5 pm, always observing the more critical of the two directions. He performed his own studies of Roswell Road and Holcomb Bridge Road, rather than use Hibbard's data, so that each left-turning movement would be correctly represented, separate from the other, in his report.

The field data collected included volume, roadside development, driveway activities, length of study area, travel time over that length, lane width, median width, and left-turning-bay width and length.

Through volumes were counted in both directions. At raised-median sites, left turns through the selected median break were counted. At a TWLTL location all vehicles that turned left over the 1000-foot study area were counted.

Both delay to left-turning vehicles and gaps available for left turns were studied simultaneously for 15 minutes. (There were never any delays observed to through traffic, except on Fulton Industrial Boulevard, where the raised-median design lacks left-turn bays at some median breaks). Left-turn delay was measured using hand-held microcomputers and the QUEDEL program written by the University of Florida to measure the delay to a queue of vehicles. Refer to Hibbard's Appendix B for details (7). At the same time as the QUEDEL study was in progress, another observer measured the gaps in oncoming traffic opposing the left turns. This was done using a metronome set to give an audible click 60 times per minute. The minimum acceptable gap was typically observed to be 5 or 6 seconds, and the study produced the amount of adequate gap time in minutes per hour.

One travel time run was performed in each direction using the floating-vehicle method. In no instance was there observed any delay caused by left-turning traffic, so a single run was considered sufficient and no analysis was performed beyond calculating the speed.

A 5-minute vehicle classification study was performed in each direction, to determine the percentages of cars and various types of trucks using the arterial.

Field-Data Analysis

Hibbard prepared scatter diagrams of the raw field-data in order to arrive at a preliminary indication of the potential for significant relationships between delay and various independent variables. Because there are a number of independent variables, and only one at a time can be shown in a two-dimensional graph, Hibbard went on to perform multiple linear regression analyses using the Biomedical Data Package (BMDP Statistical Software) installed on Georgia Tech's CYBER mainframe computer (22). Hibbard chose this program over others, such as MINITAB, because BMDP has a program known as P9R, the All Possible Subsets program. Hibbard (7) explained this program as follows:

This program begins by estimating one-variable equations with each independent variable alone. The one-variable equation with the highest R^2 is then used as the basis for two-variable models, developed from the one-variable models by adding each other variable separately to the one-variable equation. The best two-variable model is taken, and three-variable models are developed using the two-variable model. This process is continued until there are no more variables to add. The best model is chosen on the basis of the sample R^2, the adjusted R^2 and the Mallows C_p statistic.

Field-data analysis by Vargas, for his 23 sites, was similar to Hibbard's except that Vargas used directional volumes rather than volumes that had been summed for the two directions, as explained above. Also, Vargas used as an independent variable the product of a left-turning volume and the opposing (oncoming) through volume. Traffic engineers commonly calculate this product as an indicator of the need for a protected left-turn phase at a signalized intersection, so Vargas looked at the product's usefulness in estimating median-design-related delay.

Accident-Data Collection

The safety-related portion of this study was performed on the 19 sites (12 TWLTL and seven raised-median) originally approved in January, 1987. (That is, the four TWLTL sites added by Tech in April, 1987 were not included).

A complete road inventory of the 12 TWLTL and 7 raised-median sites was obtained from the computerized inventory information system at the District 7 office of the GDOT in Chamblee. On the basis of the inventory data the 19 sites were lengthened beyond the 1000-foot sections (approx. 0.2

miles) used for the delay analysis. Inventory forms (see Appendix D) were filled out for each site using the GDOT data. Repetitive visits were made to each individual site to determine cross-section consistency. This factor, the annual daily traffic (ADT), and the number of driveways per mile were used to determined the extent to which each site could be lengthened.

Summarized traffic and geometric inventories of both type of treatment are included in Tables 1, 2 and 3.

After the length of each of the 19 sites was determined by the above criteria, the accident data for the two years 1984 and 1985 were obtained from the computerized accident information system available at the downtown office of the GDOT. For each study section, the accident data for the following types of collision were obtained:

a) Angle intersect collisions
b) Head-on collisions
c) Rear-end collisions
d) Sideswipe, same direction
e) Sideswipe, opposite direction
f) Other (Pedestrians, fixed object, etc.)

Table 1. Two Way Left Turn Lane Sites Inventory for Accident Analysis

Site No.	Adjacent Land Use	State Route No.	Average Daily Traffic	Mile-Post Start	Mile-Post End	Section Length (mi)	Driveways per mile	Intersections per mile Signalized	Intersections per mile Non-Signalized	Approaches per mile	No.of Thru lanes
1T	Strip Commercial	124	17960	13.41	13.8	0.39	77	2.6	2.6	10.3	2
2T	Strip commercial	20	17768	16.83	17.69	0.86	95	3.5	5.8	11.6	2
3T	Strip Commercial	10	28300	9.21	9.91	0.70	67	2.9	2.9	5.7	6
4T	Commercial + Residential	10	27876	7.24	8.22	0.98	44	1.0	5.2	7.1	4
5T	Strip Commercial	155	21530	8.87	9.39	0.52	97	5.8	3.9	9.6	4
6T	Strip Commercial	3	45560	1.82	2.32	0.50	62	6.0	2.0	10.0	4
7T	Strip Commercial	279	45360	3.91	4.91	1.00	95	1.0	5.0	7.0	4
8T	Strip Commercial	9	32740	6.94	7.64	0.70	73	0.0	7.3	7.1	4
9T	Strip Commercial	85	36233	3.59	4.64	1.05	101	2.9	3.8	10.5	6
10T	Strip Commercial	54	32636	11.68	12.38	0.70	86	4.3	5.4	11.4	4
11T	Strip Commercial	10	43390	6.19	6.79	0.60	104	3.3	0.0	6.7	6
12T	Strip Commercial	9	38050	11.29	12.2	0.91	124	6.6	1.1	10.99	4
	Average		32284			0.74	85.4	3.3	3.8	9.0	4.2

Table 2. Raised Median Inventory for Accident Analysis

Site No.	Adjacent Land Use	State Route No.	Average Daily Traffic	Mile-Post Start	Mile-Post End	Section Length (mi)	Driveways per mile	Intersections per mile Signalized	Intersections per mile Non-Signalized	Approaches per mile	Openings per mile	No.of Thru lanes
1R	Strip Commercial	42	30000	2.28	3.04	0.76	16	1.3	2.6	3.9	5.3	6
2R	Strip Commercial	331	25096	1.23	1.94	0.71	57	1.4	5.6	11.3	9.9	4
3R	Strip Commercial	13	51409	6.98	7.15	0.17	35	5.9	5.9	17.7	5.9	6
4R	Strip Commercial	3	50703	9.77	10.76	0.99	48	0.0	8.0	9.1	4.0	4.
5R	Strip Commercial	85	36230	2.42	3.0	0.58	79	2.4	2.4	12.1	3.5	4
6R	Strip Commercial	140	43680	6.79	7.5	0.71	62	2.8	0.0	4.2	2.8	6
7R	Strip Commercial	70	35880	26.76	27.06	0.30	105	6.7	3.3	16.7	3.3	6
	Average		39000			0.60	57.4	2.9	3.97	10.7	4.96	5.1

Table 3. Statistical Comparison of Geometrics and Traffic

Category	Raised Median Lowest	Raised Median Highest	TWLTL Lowest	TWLTL Highest	Average Values R.M	Average Values TWLTL	Significant Difference 95 %
ADT	30000	51409	17768	45560	39000	32284	None
Section Length	0.17	0.99	0.39	1.05	0.60	0.74	None
Dr./mi.	16	105	44	124	57.4	85.4	Yes
Signal per mi.	0	6.7	0	6.6	2.9	3.3	None
Non Signal per mi.	0	8.0	0	7.3	3.97	3.75	None
Appr. or Street/mi.	3.9	16.7	5.7	11.6	10.7	9.00	None
No. of Thru lanes	4	6	2	6	5.1	4.2	None
Opening per mi.	2.8	9.9			4.96		

Accident Data Analysis

The accident data was sorted to give the number of damage accidents, injury accidents, persons injured, and fatal accidents. The accident data for each site was then normalized to one mile sections in order to be analyzed on a common basis.

The Biomedical Regression Programs (BMDP) developed at University of California, Los Gatos were then used to perform multiple regression analysis. The programs are available on the Georgia Tech CYBER computer. Of the various regression programs available in the BMDP package, only two were used for this analysis: BMDP-1R and BMDP-9R. The BMDP-1R includes all the specified independent variables (i.e. Driveways per mile, ADT, PHV,etc...) in the multiple regression equation. The BMDP-9R identifies the best subset of independent variables. In addition to the BMDP programs, the single regression and graph programs available in the LOTUS 1-2-3 package were used. The LOTUS 1-2-3 graphs and single regression helped to identify the relationships between each independent variable and the dependent variables (Accidents per Mile per Year and Accidents per MVM). In general, the following procedure was used:

First, Lotus 1-2-3 graphs and single-variable regression equations were developed to identify the possible contribution of each independent variable to the model and to identify the existence of outliers.

Second, the BMDP-1R program was run to find the partial t-statistic for each candidate independent variable in the model. The partial t-statistic was then tested at the significance level $\alpha = 0.05$ to check if the candidate independent variable contributes significantly to the model. The BMDP-1R program also lists a correlation table which helps in identifying the variables that are interrelated and therefore should not be included in the same model.

Third, the BMDP-9R program was run with all the candidate variables from step 2 to determine the best subset of independent variables to be included in the models.

FINDINGS

This section presents Hibbard's findings (7) for delay at the two pilot sites; Vargas' results (9) for delay at his 23 sites; Celniker's findings (8) on the effect of median type on delay at signalized intersections; and Abboud's and Vargas' results for accidents at the 19 sites.

Hibbard's Findings for Delay at the Pilot Sites

As explained earlier, Hibbard performed a Masters Special Research Problem Report that was transmitted to the GDOT by letter of October 16, 1986. He gathered and analyzed data on delay at the pilot TWLTL site (Roswell Road in Sandy Springs, a five-lane section) and at the pilot raised-median site (Holcomb Bridge Road west of Ga. 400). His procedure was summarized above.

Hibbard's principal findings were as follows:

o At the TWLTL site the delay per left-turning vehicle increased dramatically when the two-way through volume reached 2800 vph. (Hibbard did not convert this through volume into an equivalent ADT, but he could have done so easily; an urban peak-hour volume is about 10 percent of ADT, so the 2800 vph is equivalent to an ADT of about 28,000 vpd).

o At the raised-median site the delay per left-turning vehicle showed no increase as two-way through volumes increased up to the maximum observed value of over 3,700 vph, corresponding to an equivalent ADT of about 37,000 vpd. For reasons undetermined as yet, left-turn delay was found to decrease to only about 10 seconds per vehicle at high values of through volume.

o When compared at equal through volumes, the delay to left-turning vehicles at the raised-median site was consistently less than the delay at the TWLTL site.

o The maximum delay to left-turning vehicles ever observed in the study was greater at the TWLTL site than at the raised-median site. This occurred despite the fact that the raised-median site carried higher through volumes, and had a higher percentage turning left, than did the TWLTL site. The maximum delays were 39 and 30 seconds per vehicle for the TWLTL and raised-median sites, respectively.

Hibbard speculated that delay per left-turning vehicle was higher at the TWLTL site because the driveway density was much higher there (144 driveways/mi) than at the raised-median site (53).

Hibbard attempted with mixed success to use linear regression to develop a useful model that would estimate delay to left-turning vehicles from data on through volume, adequate gap time in minutes per hour, and the percentage of left-turning vehicles that must stop. The model for his TWLTL site had an R^2 of only 53 percent. He was more successful with his raised-median site, with 72 percent; however, it would not be easy for an engineer to predict future values of adequate gap time and stop percentage, so his model is hard to use.

Vargas' Findings for Delay at 23 Sites

It was explained above that Vargas prepared a Masters Special Research Problem Report (9) that was sent to the Department on June 7, 1987. As noted already, he gathered delay-data at 16 TWLTL locations and seven raised-median sites.

The largest total delays observed by Vargas in the entire project were at two raised-median sites: Tara Boulevard near Morrow, and Buford Highway just north of the interchange with I-285. Each has an ADT of about 51,000 and a driveway density of less than 50 per mile.

The largest total delays at the TWLTL sites were noticeably lower than those at the two raised-median sites just mentioned. The most-delayed TWLTL locations were found to be Buford Highway north of I-285 (just north of Longmire Road), Cobb Parkway just north of I-285, Old National Highway, and Memorial Drive at DeKalb College. At 51,000 ADT, the Buford Highway location is as busy as the two raised-median sites, and has more driveways (60 per mile), but less total delay. The other three TWLTL sites have 10 percent less traffic (about 45,000 ADT), and driveway densities ranging from 65 to 107.

Vargas' analyses began with an attempt to correlate delay with just one variable at a time. Regression analyses using only the product of the left-turn volume and the opposing (oncoming) flow were especially successful with the TWLTL sites; his model explained 81 percent of the variation from site to site. The equation is as follows:

TD = 0.008643 + 0.000002(LTV x OppVol)

where TD = total delay for TWLTL in veh-hr/hr

LTV = left-turn volume in vph, and

OppVol = opposing volume in vph

Traffic engineers will recognize that the product of these two volumes is commonly used in determining whether a signalized intersection needs a left-turn arrow because of a delay problem. The fact that we are multiplying two volumes together means that delay goes up exponentially as traffic volumes increase on an arterial with a TWLTL. That is, total delay on a TWLTL arterial goes up with the square of the flow. This relationship can be used to help understand Vargas' data for delay for TWLTLs, as follows. First, consider a "base" ADT of 15,000 to be typical of an arterial where a TWLTL is unquestionably a reasonable choice. Vargas found a total delay level of about 0.07 veh-hr/hr at that ADT. Now, if we double the ADT to 30,000, delay should quadruple to 0.28. This is very close to what he found. If instead we triple the base volume from 15,000 to 45,000, the delay should rise as the ratio of 45 squared to 15 squared, which is a factor of 9. Vargas in fact found that the delay increased from 0.07 to about 0.63.

For raised medians, Vargas found that the product of the two volumes was not nearly as well correlated with delay; only 52 percent of the variation from site to site was explained by the model. Delay was found to increase exponentially with increase in ADT, just as was found for TWLTLs. For ADT in the range of 25,000 to 35,000, delay at the raised-median sites was comparable to that observed at the TWLTL sites. However, when ADT reached 50,000, Vargas found much higher delays at two of the raised-median sites than he had encountered at any TWLTL location. Those sites were Buford Highway just north of I-285, and Tara Boulevard.

Using multiple regression analysis for both TWLTL and raised-median sites, Vargas was able to improve on his single-variable findings. For both types of designs he found that total delay was modeled best using the number of driveways per mile, the percent of left-turning vehicles that must stop, and the opposing through traffic volume. His equation for TWLTL explains 87 percent of the variation in delay from site to site, as follows:

$$TD = -0.0498 + 0.00303\ PSt - 0.00131\ Dr + 0.000002378\ M$$

where TD = total delay in veh-hr/hr/1000 ft

PSt = percent left-turn stopped,

Dr = driveways per mile, and

M = product of hourly left-turn and opposing volumes

Vargas' equation for raised medians explains 71 percent of the variation, as follows:

$$TD = 0.0719 + 0.0116728\ PSt - 0.008514\ Dr + 0.00000105\ M$$

Both equations yielded a negative coefficient for the number of driveways per mile. Parker, also, found this correlation negative (9). This goes against our expectancy and probably means that the number of driveways per mile is highly correlated with an unknown variable that has a strong negative influence on total delay.

Vargas solved his regression equations for various traffic and geometric conditions in order to determine which median design produces less delay. One conclusion follows:

- When the product of the hourly left-turn volume in one direction and the opposing volume exceeds 600,000, a raised median produces less delay, regardless of the number of driveways or the left-turn percent stopped. However, this conclusion is actually a theoretical prediction; none of the TWLTL sites had a product anywhere nearly as great as 600,000, and only one raised-median site (Buford Highway) was in that stratospheric volume level. That section of Buford Highway had much more delay than any real-life TWLTL studied, so this conclusion should not be taken as true without more research.

His next two conclusions are based on the assumption that at least 60 percent of left-turning vehicles must stop. (He found this to be true most of the time for both median designs):

o When the product of the hourly left-turn volume in one direction and the opposing volume exceeds 300,000 and there are 80 or more driveways per mile, a raised median results in less total delay. This conclusion, like the previous one, needs to be accepted cautiously. The one TWLTL site (Memorial Drive at DeKalb College) with a product over 300,000 actually had less delay than the one raised-median site with so high a product (Buford Highway). However, the regression equation predicts that Buford Highway would greatly improve in delay if the driveways were increased from the actual 35 to over 80.

o When the product of the hourly left-turn volume in one direction and the opposing volume is less than 200,000 and there are less than 50 driveways per mile, a TWLTL results in less total delay. Our data show that the ADT can be as high as 50,000 without exceeding a product of 200,000, as for example at Tara Boulevard and Holcomb Bridge Road (both raised-median sites with substantial delay). Moreover, the TWLTL section with the highest ADT (Memorial Drive near I-285, ADT 55,400) did not exceed a product of 121,000 during our observations. So, the specification of a product of less than 200,000 in no way limits the category to low-ADT arterials. Inasmuch as this product is useful over a wide range of ADT, and since our observations included sites of both types with driveways on either side of, and close to, 50 per mile, this conclusion ought to be valid for the purposes of the Department.

Celniker's Findings on Delay at Signalized Intersections

As explained earlier, Celniker performed a project leading to a Masters Special Research Problem Report (8) that was transmitted to the GDOT by letter of October 16, 1986. His work was quite different from that performed by Hibbard and Vargas, so his procedure needs to be explained prior to discussing his findings.

Celniker studied only one location, namely the TWLTL site on Roswell Road between Hilderbrand Road and Sandy Springs Place. (That is the same portion of Roswell Road used by Tech's other researchers). First, he assigned each driveway to a "driveway group". All driveways in a group are connected to one another, so that a driver can turn into any one of them to reach any of the businesses served by the common parking lot. Six driveway groups were designated along the west block face, and four along the east face. Then he performed extensive volume counting, during six times of day, of the left turns into and out of each driveway group. Volumes at the intersections with Hilderbrand Road and Sandy Springs Place were also counted during the same six periods.

Celniker then developed computer models for four median-type scenarios, as follows:

o Model 1 - Existing situation, with TWLTL. Observed volumes were entered into the model without change.

o Model 2 - Continuous raised median with no openings but with left-turn lanes cut into the median at the intersections. All mid-block left-turning vehicles that used the TWLTL in Model 1 are modeled to go to an intersection, make a U-turn, and complete the desired movement.

o Model 3 - Raised median with one opening in the middle of the block, with left-turn cut-outs.

o Model 4 - Same as Model 3, except that U-turns are prohibited at the intersections; drivers that in Model 3 were allowed to make these U-turns are instead modeled as through traffic at the intersections and as U-turns at the next median opening.

For Models 2,3 and 4, all of which include raised medians, Celniker widened Roswell Road to include shoulders to ease the U-turns. He also took into account the fact that the pedestrian-minimum-green timing at the signalized intersections could be calculated to be enough only to allow the pedestrian to reach the raised median. He therefore was able to reduce minimum green times in Models 2,3 and 4 to 3 seconds less than that used in Model 1. That adjustment tended to reduce intersection delay in the raised-median models.

Celniker then utilized the Signal Operations Analysis Package (SOAP) to analyze intersection counts and determine the total intersection delay for each model. As compared to the TWLTL model 1, raised-median models 2 and 3 caused large percentage increases in intersection delay, particularly at Sandy Springs Place. Model 4, however, increased delay at Hilderbrand by less than 1 percent. At Sandy Springs Place, intersection delay increased 6 to 12 percent in Model 4, but decreased by 5 percent during 4:00 to 6:00 pm and decreased by 1 percent on weekends and holidays. The reason for the reduction during these two periods is that traffic exiting Sandy Springs Place is so low. The reduced ped-minimum green timing (used with the raised median) is operative under low vehicle-volume conditions, so the shorter cross-street greens reduce intersection delay more than rerouted traffic increases it. Celniker concluded as follows:

> Model 4 clearly maximizes the benefits of a raised median from the standpoint of intersection delay. Delay-inducing exclusive left-turn phases are reduced sharply by banning U-turns, while the increase in through traffic has small effect. The other benefits of raised medians remain--separating opposing traffic, limiting midblock left turns to a single point, and restoring a perception of safety.

Celniker also determined the delay to rerouted vehicles, defined as the delay in driving the rerouted distance, plus the delay at an intersection, plus the delay while waiting for an acceptable gap in oncoming traffic to make a U-turn or left turn. (Of course, Celniker took into account that motorists using a TWLTL must wait for an acceptable gap, also). He found that each of the raised-median models (2,3 and 4) increased delay sharply over the TWLTL model (1). Model 3 had the least of the increases because it has a median opening and allows U-turns at intersections. Even for Model 3, however, delay was two to five times greater (depending on time of day) than for the TWLTL model.

Celniker concluded that, at the study site, a raised median would increase delay, primarily because of the lack of interconnection of the driveways and parking lots. He concluded that the best way to minimize the delay induced by raised medians is to persuade land owners to allow access between neighboring parking lots. He could come to no conclusion on the merits of prohibiting U-turns at signalized intersections; this control reduces total delay at the intersection but greatly increases delay to rerouted vehicles.

Findings by Abboud and Vargas at 19 Sites

Tables 4 and 5 give the summaries and the averages of the two types of treatments for all types of collisions. Table 4 shows that the TWLTL sites averaged 163.0 accidents per mile per year, while Table 5 indicates that the corresponding value for the raised-median sites was 130.9. This is a reduction of 20 percent. Accidents per million vehicle miles of travel were 13.6 and 9.3 for the TWLTL and RM

Table 4. Summary of Accidents by Types for TWLTL Sites

Site No.	Type of Treatment	Section Length	ADT	Angle Intersect	Head On	Rear End	Sideswipe Same Dir.	Sideswipe Opp. Dir.	Other Acc.	Accidents per Mile per Year	Accidents per million Vehicle mil
				-----------Accidents Per Mile Per Year-----------							
1T	TWO WAY LEFT TURN LANE	0.39	17960	20.5	0.0	17.9	6.4	1.3	0.0	46.1	7.0
2T		0.86	17768	48.5	2.9	30.8	7.6	2.9	4.1	96.7	14.9
3T		0.70	28300	32.1	0.7	20.0	8.6	0.7	6.4	68.5	6.6
4T		0.98	27876	10.7	0.0	2.6	3.1	0.5	2.0	18.8	1.9
5T		0.52	21530	42.3	1.0	40.4	11.5	2.9	6.7	104.0	13.3
6T		0.50	45560	375.0	14.0	188.0	51.0	4.0	11.0	643.0	38.7
7T		1.00	45360	87.0	4.0	47.5	12.0	3.5	3.5	157.0	9.5
8T		0.70	32740	34.2	0.0	27.1	18.6	0.7	12.9	93.5	7.8
9T		1.05	36233	131.0	6.2	71.0	31.4	7.6	5.2	252.0	19.1
10T		0.70	32636	51.4	2.1	43.6	15.0	1.4	4.3	117.0	9.9
11T		0.60	43390	90.8	2.5	112.5	23.3	4.2	11.7	245.0	15.5
12T		0.91	38050	114.8	1.6	63.2	15.9	9.3	7.1	212.0	15.3
			Average:	82.6	2.9	51.8	16.4	3.8	6.0	163.0	13.6

Table 5. Summary of Accidents by Types for R.M. Sites

Site No.	Type of Treatment	Section Length	ADT	Angle Intersect	Head On	Rear End	Sideswipe Same Dir.	Sideswipe Opp. Dir.	Other Acc.	Acc per Mile per Year	Acc per Million Vehicle Mil
				-----------Accidents Per Mile Per Year-----------							
1R	R	0.76	30000	10.5	1.3	12.5	8.6	0.0	4.6	37.5	3.4
	A										
2R	I	0.71	25096	12.7	0.0	9.9	3.5	0.0	5.6	31.6	3.5
	S										
3R	E	0.17	51409	211.8	5.9	88.2	38.2	14.7	2.9	361.0	19.3
	D										
4R		0.99	50703	49.0	0.5	74.2	21.7	2.5	13.6	161.0	8.7
	M										
5R	E	0.58	36230	90.5	1.7	64.7	12.9	1.7	2.6	174.0	13.2
	D										
6R	I	0.71	43680	64.8	0.0	50.7	10.6	0.7	3.5	130.0	8.2
	A										
7R	N	0.30	35880	151.7	10.0	66.7	43.3	6.7	13.3	291.0	22.3
			Average:	58.2	1.5	47.0	15.4	2.0	7.0	130.9	9.3

sites, respectively, a reduction of 32 percent. Both of these differences are statistically significant. The significance level used is 0.05.

This implies that we can say with 95 percent confidence that the types of medians have significantly different averages for the different types of collisions. The TWLTL median treatment exhibited slightly more average angle intersect, head-on and rear-end accidents than the raised-median treatment. The TWLTL median treatment also exhibited less average "sideswipe opposite" and average "sideswipe same direction" than the raised-median treatment.

A severity analysis of the two types of treatment was also conducted. Tables 6 and 7 summarize on a per-mile basis the number of fatal accidents,fatalities, injury accidents, persons injured, and property-damage-only accidents. Although there were no fatal accidents with either design, the RM sites were safer than the TWLTL sites in terms of number of injury accidents, persons injured and property-damage-only accidents. Percentage-wise, the RM sites were lower by 16, 15 and 20 percent in those three categories. These are all statistically significant at the 0.05 level. (Table 9, explained later, includes a comparison of number of injury accidents on a "per million vehicle mile" basis).

A similar significance test was done on the accident

Table 6

Accident Severity for TWLTL Sites

Site No.	Type of Treat.	Fatal Acci.	Fatalities	Injury Acci.	Persons Injured	Property Damage
		------Accidents	Per Mile	Per Year------		
1T	T	0	0	10.0	19.0	86.0
2T		0	0	17.0	28.0	148.0
3T		0	0	14.0	19.	94.
4T	W	0.5	0.5	2.0	3.0	21.0
5T		0	0	21.0	30.0	141.0
6T *		0	0	139.0	196.0	1034.0
7T	L	0	0	47.0	65.0	304.0
8T		0	0	21.0	27.0	121.0
9T		0	0	50.0	73.0	380.0
10T	T	0	0	28.0	41.0	188.0
11T		0	0	55.0	79.0	355.0
12T		0	0	37.0	57.0	308.0
			Averages =	34.9	50.5	252.5

* Site 6T Cobb Pkw was later removed from the analysis because its accident frequency was so different.

Table 7

Accident Severity for Raised Median Sites

Site No.	Type of Treat.	Fatal Acci.	Fatalities	Injury Acci.	Persons Injured	Property Damage
		------Accidents	Per Mile	Per Year-------		
1R	R	0	0	10.0	14.0	57.0
2R	A	0	0	6.0	8.0	38.0
3R	I	0	0	52.0	85.0	506.0
4R	S	0	0	37.0	39.0	168.0
5R	E	0	0	43.0	68.0	321.0
6R	D	0	0	27.0	50.0	237.0
7R	M.	0	0	76.0	123.0	579.0
			Averages =	29.4	42.9	201.6

Table 8
Accident Data Summary for the Types of Collisions

Percentages Based on Accidents Per Mile Per Year

Types of Collision	TWLTL %	Raised Median %	Significant Difference (= 0.05)
Angle Inters.	50.5	44.4	None
Head - On	1.8	1.1	None
Rear - end	31.7	35.9	None
Sideswipe Same Dir.	10.0	11.7	None
Sideswipe Opp. Dir.	2.3	1.5	None
Other	3.7	5.3	None
	100.0	100.0	

Table 9

Accident Rates Summary

Category	Average Value TWLTL	Raised Median	Significant Difference
No. of Sites	12	7	-
Accident Rate per MVM*	13.6	9.3	Yes
Accidents per mile per year	163.0	130.9	Yes
Injury Acc. per MVM	2.9	2.1	Yes

* Million vehicle miles of travel

data summary listed in Table 8. None of the percentages for the two types of treatments and for the different types of collisions were found to be statistically different.

Table 9 is important as a summary of the main findings from Tables 4 through 7. The raised-median design is seen to average only 9.3 accidents per MVM, as compared to 13.6 for the TWLTL design, a difference of 32 percent. Accidents per mile per year are lower by 20 percent for the raised-median choice. Injury accidents per MVM are lower by 28 percent.

The accident data in Tables 4 through 9 include the intersection accidents on all approaches and not just the mid-block accidents. This procedure took into account the fact that a raised-median design tends to route traffic to the intersections.

The regression analysis steps listed earlier, revealed that for the APMVM equations only the independent variable "Signals per Mile" contributes significantly to that model for both types of median treatments. The APMVM equations were dropped from the analysis. This analysis also reveals the existence of an outlier namely site 6T, Cobb Parkway, which had an abnormally high number of APMPY and APMVM. This site was removed from the analysis.

For the APMPY model, regression analysis using Lotus 1-2-3, BMDP1R and BMDP9R (best subset of independent variables) resulted in the following models:

For traversable medians;	R^2	Std. Error
APMPY = -153.46 + 0.053 PHV + 1.78 DR	0.89	49.4 acc/mi

For raised medians;	R^2	Std. Error
APMPY = -175.21 + 0.085 PHV + 34.5 SIG	0.95	20.2 acc/mi

where APMPY = accidents per mile per year

PHV = peak hourly volume

SIG = signalized intersections per mile

DR = driveways per mile

The two models were tested at the significance level of = 0.05 and were both found to be highly significant.

The two models listed above can be used to give a general idea of the number of accidents per mile to be expected on the two types of median treatments. The only variables needed for this comparison are PHV, signalized intersections per mile and driveways per mile. The comparison should help in the decision of which type of treatment is better suited for the given conditions.

A comparison of the expected number of accidents for specific geometric and traffic conditions for both median treatments is given in Table 10. As expected, the accident frequencies for both median types rise with increases in the peak-hour volume, number of signalized intersections per mile, and number of driveways per mile. It can be seen

Table 10
TWLTL and R.M. Expected Accidents per mile per year

Signals Per Mile	Driveways Per Mile	PHV = 1500		PHV = 2000		PHV = 2500		PHV = 3000		PHV = 3500	
		Raised Median	TWLTL	Raised Median	TWLTL	Raised Median	TWLTL	Raised Median	TWLTL	Raised Median	TWLTL
	40	21.3	-2.8	63.8	23.7	106.3	50.2	148.8	76.7	191.3	103.2
2	80	21.3	68.4	63.8	94.9	106.3	121.4	148.8	147.9	191.3	174.4
	120	21.3	139.6	63.8	166.1	106.3	192.6	148.8	219.1	191.3	245.6
	40	90.3	-2.8	132.8	23.7	175.3	50.2	217.8	76.7	260.3	103.2
4	80	90.3	68.4	132.8	94.9	175.3	121.4	217.8	147.9	260.3	174.4
	120	90.3	139.6	132.8	166.1	175.3	192.6	217.8	219.9	260.3	245.6
	40	159.3	-2.8	201.6	23.7	244.3	50.2	286.8	76.7	329.3	103.2
6	80	159.3	68.4	201.6	94.9	244.3	121.4	286.8	147.9	329.3	174.4
	120	159.3	139.6	201.6	166.1	244.3	192.6	286.8	219.9	329.3	245.6

that for most situations the TWLTL is the safer design. The raised-median design was associated with fewer accidents only when there were 2 or fewer signalized intersections per mile, 80 or more driveways per mile, and the two-way peak-hour volume was less than 3000.

COMPARISONS WITH RESULTS OF EARLIER STUDIES

This section discusses the extent to which the findings of the present study are in harmony with, or represent a departure from, those of previous researchers. Results for both delay and accidents are considered.

Delay Comparisons

The literature is so weak in the area of delay associated with the two types of median designs that it is difficult to make comparisons. Earlier herein a review of literature suggested an upper limit of 25,000 to 40,000 ADT for the TWLTL design. Hibbard's findings at the two pilot sites suggested that the delay per left-turning vehicle at a TWLTL site increases very significantly when the ADT exceeds about 28,000. However, Vargas found that this is true for both kinds of median design; delay goes up exponentially with increase in ADT. Vargas found delay to be about the same for both designs, ADT for ADT. However, he found that when ADT reaches about 50,000 a raised-median design may experience much more delay than a TWLTL.

This finding by Vargas seems to be in harmony with the work of Tech student Celniker, who found that changing a section of Roswell Road from TWLTL to a raised-median design would increase delay.

Safety Comparisons

Our models were compared to the ones obtained from the Virginia study (9), which developed the following equations to predict accidents per mile for the two types of treatment:

For raised median;

$$Ar = 8.040\ Sig + 0.00155\ ADT - 0.0228\ Dr - 0.00000920\ Pop - 12.718$$

For traversable medians;

$$At = 5.432\ Sig + 0.00173\ ADT + 2.157\ St - 0.0000056\ Pop - 28.797$$

where Ar = annual accidents per mile for raised medians

At = annual accidents per mile for TWLTL

SIG = signalized intersections per mile

ADT = average daily traffic

Dr = driveways per mile

St = streets per mile

Pop = area population

A comparison of the Virginia and the Georgia Tech models is presented in Tables 11 and 12. It can be observed that the Virginia model highly underestimates the amount of Atlanta accidents per mile per year for annual daily traffic (ADT) higher than 30,000 for raised median and TWLTL treatments. Analysis of the errors of estimates for the Georgia Tech model listed in Tables 11 and 12 shows that the TWLTL model does a better job in estimating the number of accidents per mile per year. This could be mainly due to the greater number of cases in the TWLTL model.

Table 11
Comparison of Virginia and Georgia
Model for Raised Median

Site Number	SIG	DR	PHV	ADT	Exist APMPY	Predicted APMPY	Error	Virginia Model	Error
1R	1.3	16	2012	30000	37.5	40.6	+3.1	41.0	+3.5
2R	1.4	57	2297	25096	31.6	68.3	+36.7	33.3	+1.7
3R	5.9	35	4034	51409	361	371	+10.0	110.8	-250.2
4R	0.0	48	3186	50703	161	95.7	-65.3	62.0	-99.0
5R	2.4	79	3210	36230	174	180.4	+6.4	58.1	-115.9
6R	2.8	62	3030	43680	130	178.9	+48.9	73.3	-56.7
7R	6.7	105	2500	35880	291	251.2	-39.8	91.5	-199.5

Table 12
Comparison of Virginia and Georgia
Model for TWLTL

Site Number	SIG	DR	PHV	ADT	St.	Exist APMPY	Predicted APMPY	Error	Virginia Model	Error
1T	2.6	77	1404	17960	10.3	46.1	57.8	+11.7	36.9	-9.2
2T	3.5	95	1116	17768	11.6	96.7	74.5	-22.2	44.2	-52.5
3T	2.9	67	1827	28300	5.7	68.5	62.4	-6.1	46.5	-22.0
4T	1.0	44	1424	27876	7.1	18.8	0	-18.8	38.4	+19.6
5T	5.8	97	1956	21530	9.6	104	122.6	+18.6	58.9	-45.1
7T	1.0	95	3060	45360	7.0	157	177.5	+20.5	68.5	-88.5
8T	0.0	73	2706	32740	7.1	93.5	119.7	+26.2	41.4	-52.1
9T	2.9	101	3966	36233	10.5	252	236.2	-15.8	70.5	-181.5
10T	4.3	86	2355	32636	11.4	117	124.2	+7.2	73.9	-43.1
11T	3.3	104	3613	43390	6.7	245	222.8	-22.2	76.9	-168.1
12T	6.6	124	2733	38050	10.9	212	211.7	-0.3	94.7	-117.3

CONCLUSIONS

Regarding delay, the following conclusions can be drawn from the present research:

o Overall, it was found that the difference in the two designs in delay for turning vehicles was insignificant.

o ADT alone is not a good indicator of the delay to be expected from either median design. Delay increases exponentially with ADT for both designs. However, when ADT becomes high, around 50,000, there is a potential for much greater delay with a raised median than with a TWLTL. This potential is a reality at Tara Boulevard and Buford Highway just north of I-285.

o The TWLTL design results in less total delay to left-turning vehicles than does the raised median design in those locations where the product of the hourly left-turn volume (in one direction over a 1000-foot section) and the hourly opposing (oncoming) volume is less than 200,000 and there are fewer than 50 driveways per mile. There seems to be no ADT equivalent for the 200,000.

o Just as reported in previous research by others such as Parker in Virginia (9), the present research found that delay decreases with increasing driveway density, for both median types. It seems that the number of driveways per mile is highly correlated with an unknown variable that has a strong negative influence on total delay.

o When a raised-median design is selected, delay at signalized intersections can be minimized by prohibiting U-turns there, forcing them to be made at the next median opening. Delay-inducing exclusive left-turn phases are reduced sharply by prohibiting the U-turns, while the increase in through traffic has small effect.

o Even if a mid-block median opening is provided and U-turns are allowed at intersections, a raised-median design will increase delay to left-turners by a factor of two to five over what they would experience with a TWLTL.

o The key to reducing delay to left-turners using a raised-median facility is to provide access between contiguous parking lots. Normally this is done by means of service roads paralleling the arterial and connecting to it at the median openings.

o More time will be required to substantiate all of these findings and conclusions regarding delay.

Regarding safety, the following conclusions can be drawn from the present research:

o The raised-median design, as compared to the TWLTL choice, is lower by 20 percent in accidents per mile per year, and lower by 32 percent in accidents per million vehicle miles. Injury accidents per MVM were reduced by 29 percent. These differences are statistically significant at the 95 percent confidence level.

o The raised-median design, as compared to the TWLTL choice, is lower by 16 percent in injury accidents, 15 percent in persons injured, and 20 percent in property-damage-only accidents, all of which were calculated on a "per mile" basis.

o There is no significant difference between the median designs in the percentage distribution of the various types of vehicular collisions (right angle, rear-end, etc.).

o The raised-median design showed a lower accident frequency where there were 2 or fewer signalized intersections per mile, 80 or more driveways per mile, and a two-way peak-hour volume of less than 3000. For all other conditions within the study scope the TWLTL resulted in fewer accidents.

o As is the case with the delay research, more time will be required to substantiate the findings and conclusions herein.

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Appendix A

Approved Work Plan

APPROVED WORK PLAN

PHASE I: Design of Methods of Evaluation

A. Complete a review of literature relating to median treatments.

1. Complete an annotated bibliography on median treatments.
2. Prepare a detailed literature review.

B. Develop a method of examining roads including a preliminary list of factors for consideration.

1. In cooperation with the GDOT Planning and Programming Division, determine locations of roads with TWLTLs and medians and the speed limits and volumes for these roads.
2. Determine preliminary list of factors to be quantified by data collection.
3. Use photologs to determine road alignment, major intersection spacing, and the level and type of roadside development (including the number of driveways per mile).
4. Request GDOT permission to visit sites lacking inventory or photolog data.
5. Select methods to measure volume, stops, delay and overall travel speed during peak periods.

C. Select field data collection sites, gain approval from the GDOT.

1. Review inventory of sites to identify potentially excessive volumes. Request GDOT permission to visit sites. Count midblock volumes, record driveway activity, and videotape any operational problems observed.
2. Select a TWLTL and a site with a median to be used as the

pilot sections for use in testing data-collection procedures.

3. Plan sampling details for measurement of through and left turning volumes, conflicts, stops, delay and overall travel speeds. Determine observation section length and location-specific data needs (signalized intersection and delay data). Also determine sampling methods for determination of delay to vehicles desiring to turn left onto road from driveways.
4. Purchase microprocessor-based hand tallies, repair air-tube-type volume counters, prepare van for field studies, repair computer equipment.
5. Hire and train field observers.
6. With GDOT permission, collect data from Pilot Sections to determine if data collection techniques are adequate.
7. Select statistical techniques for office analysis.
8. Apply statistical techniques to determine the number of field data collection sites needed. Preliminary estimate is 10 TWLTL sites and 6 median-related sites, but this is subject to change based on Tech's experience in locating suitable sites, and on limitations of budget and time. These sites will be chosen based on two criteria: ADT and level of roadside development (measured in driveways-/mile). Optimally, TWLTL sites would fall into three ADT categories (less than 18,000, between 18,000 and 30,000, and greater than 30,000) and median sites into two volume categories (less than 30,000 and greater than 30,000).

For each volume category, sites would be selected with driveway densities in three ranges (less than 50/mile, between 50 and 100/mile and greater than 100/mile).

9. Meet with GDOT; together make final selection of field data collection sites and data to be collected.

PHASE II: Collection of Data and Evaluation

A. Select computer type and statistical software; design coding forms.

C. Collect field data at approved sites and perform office coding concurrently.

D. Develop concept of Median Performance Index (MPI). This will be an linear combination of stops and delay which will indicate the effectiveness of a specific median treatment on a specific road, where a large MPI would indicate a large amount of stops and delay. The MPI would also take into account the delay of the vehicles turning onto the road.

E. Perform a capacity analysis of TWLTLs. Also determine effects on capacity caused by vehicles turning onto the road from driveways.

PHASE III: Report Preparation

This phase will result in a written report which will document all details of the collection of data and its evaluation. Based upon the results presented in the report, further research on this topic may be desired.

Appendix B

Review of Literature

REVIEW OF LITERATURE

Project No. E-20-G03 (R6144-0A0)
Criteria for Two-Way Left-Turn Lanes
Versus Other Median Treatments
Task Order No. 6 Under BOA No. 90 Dated
1/9/84

Prepared by Georgia Tech, Civil Engineering for Georgia DOT
August, 1986

Over the thirty years since the first Two-Way Left-Turn Lane (TWLTL) was installed considerable research on the TWLTL's operating characteristics has been done. Around the time of the installation of the first TWLTL, highway engineers had been removing bi-directional passing lanes because of very high head-on collision rates. Consequently, many engineers were reluctant to use another road configuration involving a lane used by vehicles traveling in both directions.

Because of the accident problems experienced by the bi-directional passing lanes, TWLTLs were opposed by traffic engineers who felt that TWLTLs would have similarly high head-on accident rates. As a consequence, early TWLTL studies concentrated on two major points: improper (i.e., potentially dangerous) use of TWLTL's and the comparison of before-TWLTL and after-TWLTL accident rates. Typically, head-on collision rates were studied to see if they increased after TWLTL installation. Even though an early study on TWLTL operation showed that head-on collisions were an uncommon occurrence and of little concern (1), later studies included head-on collisions as part of their accident analysis.

During the late 1960s the increase in commercial strip

development in the form of fast-food restaurants and shopping centers produced a need for some traffic engineering technique which could handle the increased midblock left-turn volume. The TWLTL was seen as an safe and effective way to handle midblock left turns. As TWLTL use increased, so did the desire to learn more about its operating characteristics. Two projects conducted during the mid-1970's addressed TWLTL operating characteristics.

Nemeth's research at the Ohio State University (2) specifically focused on the operating characteristics of TWLTLs, and also included a literature review summarizing previous TWLTL research. The other major research concerning median treatments was performed by Glennon for the FHWA in 1975 (3). Glennon's results allowed the user to determine the optimum median treatment, given the ADT and level of roadside development of a certain road. would determine the optimum median treatment.

Since the mid-1970's TWLTLs have continued to be the focus of much research. In 1979, Parker used regression equations to determine the best type of median treatment based on ADT and accident rates (4). Other recent research has used computer simulation in an effort to simulate arterial operation (5, 6, 7).

In an effort to organize a TWLTL and median treatment based literature review, the literature will be grouped as follows: 1) Accident Research, 2) Operational

Characteristics, 3) Volume/Capacity Research, 4) Computer Simulation, 5) Comparison of TWLTLs with Other Median Treatments, and 6) Other Relevant Literature.

ACCIDENT RESEARCH

Accident-oriented research forms a large part of the TWLTL body of knowledge for two major reasons: accident reports are easy to find for statistical analysis also, early opponents of TWLTLs used high accident rates as a defense against TWLTL use. Accident research usually focused on one of two basic methodologies: comparison of accident rates before and after the installation of a TWLTL, or determination of TWLTL effectiveness based on benefit-cost ratios.

Accident Rate Reduction Research

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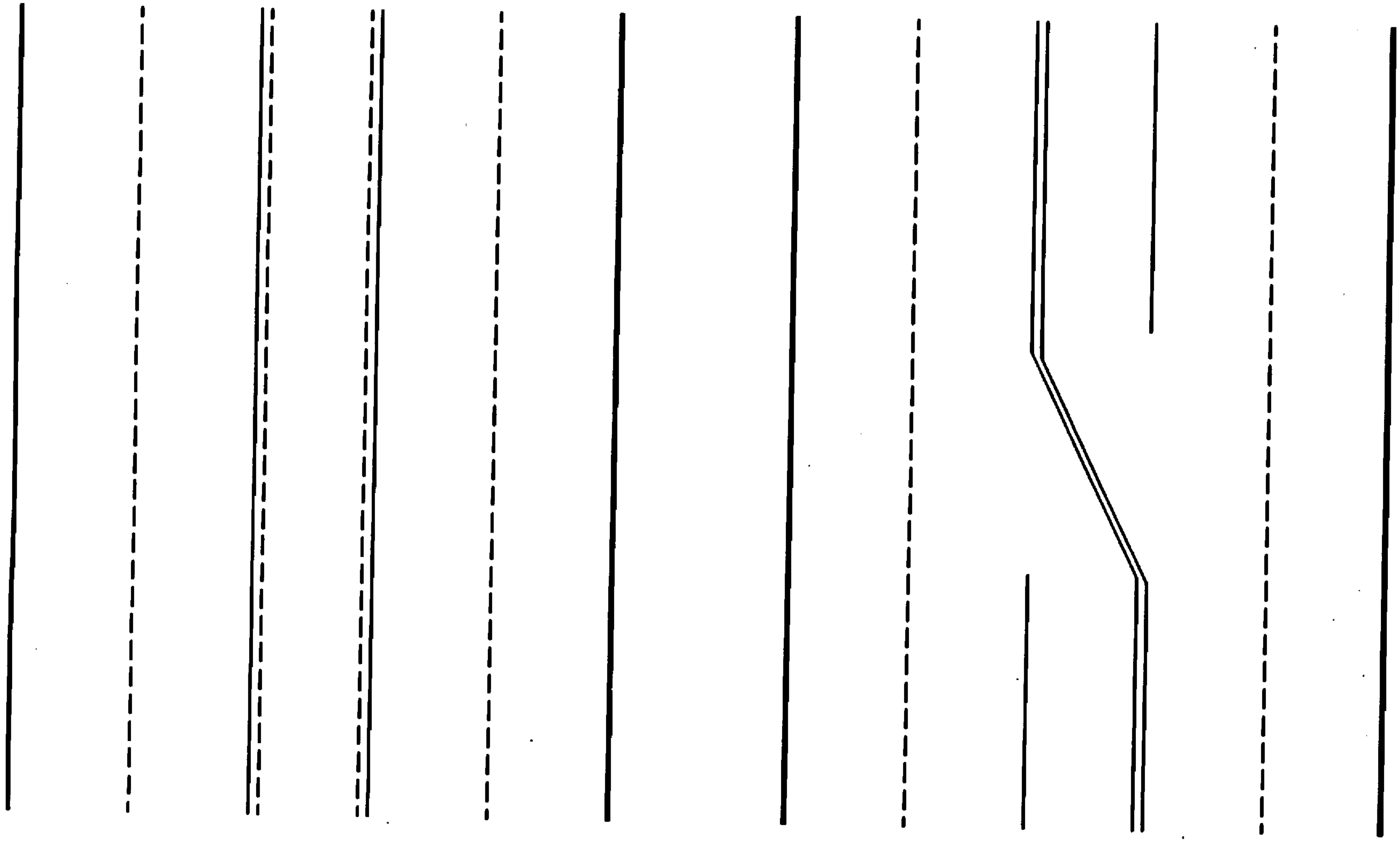

TWO-WAY LEFT-TURN LANE

ALTERNATING LEFT-TURN LANE

FIGURE 1 - DIFFERENT TYPES OF LEFT-TURN LANES

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Benefit-Cost Ratio Research

Accident-oriented research using benefit-cost ratios as criteria were often presented as an extension of the accident-rate reduction research so as to justify a certain median treatment on the basis of the benefit-cost ratio of the improvement. As it is with any accident-oriented research, the major difficulty associated with benefit-cost ratios is the difficulty of estimating the cost of the "typical" accident. It is not terribly

difficult to determine the average cost of a property damage only accident; placing a "price on someone's head" is an entirely different matter. The difficulty in determining human worth is a good reason why much accident-oriented research stops after it states the potential reduction in accidents associated with a given median treatment; it is left to the engineer using the results to translate that reduction into a "dollars and cents" quantity.

Glennon and Harwood's research (16) adopted this method in analyzing the choice of median treatments. The final results took into consideration ADT and the level of development along the arterial and presented the results in a tabulated form. Their results showed that a TWLTL was preferred even for high levels of ADT and roadside development. This result implies no limit on the traffic volumes for efficient TWLTL operation.

Several potential problems exist with Glennon and Harwood's techniques and the authors address them. The benefit data was based on vehicular delay and accident reduction data, and the accident reduction data was based on regression equations, which are not necessarily accurate predictors of real-world activity. Also of concern is that the cost information was based on 1974 data and must be adjusted to compensate for inflation.

Benefit-cost ratios typically favor TWLTLs since the initial construction cost is low with respect to other

median treatments (raised or depressed medians, for instance). TWLTLs can be constructed on relatively narrow right-of-way. In some situations, TWLTLs can be created by restriping a 2- or 4-lane highway with little or no widening.

Thakkar (17) also used a benefit-cost analysis to determine that TWLTLs were economic and safe alternatives on highly-developed arterials. The low construction cost of a TWLTL again helped to make it a favorable median treatment.

OPERATIONAL CHARACTERISTICS

In an effort to determine the effect of TWLTLs on the "typical" vehicle traveling on an arterial, research has also concentrated on the operational characteristics of TWLTLs. Nemeth was one of the major researchers in this area. He analyzed different roadway sections, using before and after TWLTL installation running times as the TWLTL's measures of effectiveness (18). Nemeth also analyzed TWLTL effectiveness in terms of weavings and braking (mentioned above). In two out of three cases TWLTLs were found to increase running speeds when compared with the "before" case (prior to TWLTL installation). Only in the case where a four-lane highway was restriped as a three-lane highway did the quality of flow suffer.

Harwood and St. John's research on operational improvements on two-lane highways (19) also dealt with the effectiveness of TWLTLs installed on 2-lane roads. The results of their research were presented in the form of a regression equation used to predict the delay per left-turning vehicle as a function of the opposing volume. While this seems a logical relationship, the R^2 for his equation was only 0.32, and a raw data plot showed the presence of two highly influential points at large volumes.

VOLUME/CAPACITY LITERATURE

A large portion of available literature addresses, in one form or another, the relationship between volume and median treatment. In this aspect of median treatment choice, much of the literature is informal in nature, with the author stating certain volume ranges which have been observed to operate adequately. The remainder of the applicable literature is more academic in nature, involving some sort of study which attempted to relate volumes and operating characteristics.

The concept of a capacity on a road with a TWLTL is expressed casually in much of the literature. Fisher (20) observed "satisfactory at best" operation of seven-lane facilities with ADT around 40,000. This statement concurs favorably with Lebel's statement (21) that a

five-lane (four through lanes plus a TWLTL) section near Grand Rapids, with ADT around 40,000 is not operating as well as it did at lower volume levels. The preferred treatment for the Grand Rapids example is a "boulevard-type design," with the through lanes separated by a raised, curbed median and left-turn pockets at intervals. The actual reconstruction of the Grand Rapids arterial also included reorganization of access driveways and roadside signs in an effort to reduce driver confusion (22).

Although Glennon's work (23) was mainly accident oriented, his TWLTL "warrant" was for ADT between 10,000 and 20,000. Similarly, McCormick's accident work (24) was done on highways with ADT's of around 20,000. In addressing accident experience on seven-lane roads, Parker (25) mentioned that the accident rates on seven-lane roads, with ADT around 20,000, are not significantly higher than those on five-lane roads.

Nemeth's work (26) during the mid-1970s included a literature search which highlighted several comments concerning the optimum volume range for TWLTL-equipped roads. TWLTLs use was documented over a range of ADT extending from 8,000 to 31,000. At all volume levels TWLTL's were found to reduce the accident rates.

Nemeth cites a literature search by the Georgia Section of the ITE which recommended TWLTL use on five-lane roads with ADTs between 10,000 and 25,000. Three-lane sections

were recommended for ADTs below 10,000. This search also concluded that the benefits of a TWLTL (lower accident rates, lower left-turn vehicular delay, lower through vehicle delay) become questionable as the volumes approach capacity due to the lack of gaps in opposing traffic needed to make left turns (27).

The state of Washington uses TWLTLs on multilane roads with ADT between 10,000 and 25,000 and on two-lane roads between 5,000 and 12,500 (28). Their upper limit of 25,000 ADT is echoed by Thompson (29) for a five-lane road. Thompson goes on to state that 40,000 ADT exceeds the practical capacity of a seven-lane road, which he concludes on the basis of observing a seven-lane road with 40,000 ADT in Grand Rapids.

Sawhill and Hall state that "traffic volumes as such are not always found to be a warrant, but volumes approaching roadway capacities in either direction may be a reason for not installing the TWLTL, more important would be the observations of time gaps or sufficient length for left turn movements to be accomplished." (30).

Both the old and new Capacity Manuals address the capacity characteristics of roads with various median treatments. One states that because a raised median reduces the "friction" between opposing directions of traffic, a road with a raised median will have a higher capacity than a five-lane road (31). While the new Capacity Manual (32) recognizes that midblock congestion

can be the limiting capacity factor, it states no method for midblock capacity determination. Elsewhere, the new manual states that a road with a TWLTL will operate somewhere inbetween an undivided and a divided road. The "Adjustment Factor for Type of Multilane Highway and Development Environment" is an attempt to quantify the effects of roadside development and median treatments in the calculation of highway capacity. This factor is determined subjectively and has no numerical guidelines. Harwood's recent research on median alternatives (33) states the preferred condition for TWLTLs: low to moderate through volumes, high left-turn volumes, high driveway densities and high rear-end and right-angle accident rates. He states that delay reduction (compared with no TWLTL) is modest at low volume levels and large at large flow rates. He also states that little work has been done to establish volume ranges for the installation of TWLTLs.

COMPUTER SIMULATION

Since the mid-1970's computer simulation of arterial operation has been a popular method to model operating characteristics under a variety of conditions. Heikal developed the ARTSIM program (34) to model arterial flow at varying levels of through volume, left-turn volume, and roadside development. The level-of-service concept

propsed by Heikal is based on the friction between left-turning vehicles and through vehicles and is measured in the average number of stops per vehicle. ARTSIM was developed to compare the quality of arterial flow with and without a TWLTL, and it could be used to model TWLTLs under a variety of circumstances as well as boulevard-type arterial design.

Similarly, McCoy (35) used the General Purpose Simulation System (GPSS) language to simulate the operation of a three-lane facility. GPSS allows the user to specify different volumes and driveway densities. McCoy used the reduction in stops and delay as his measures of effectiveness.

The NETSIM computer program was proposed for the determination of the quality of urban arterial flow (36). It involved considerable data collection with respect to the geometrics of the arterial. Careful data collection would ultimately provide a realistic computer model. Although specific references to TWLTLs were not made, NETSIM could be easily adapted to research aimed at quantifying the operating characteristics of urban arterials with TWLTLs.

McCoy's latest simulation work, TWLTL-SIM, written with GPSS was written to simulate a 5-lane section with TWLTL. Using Gerlough and Wagner's gap acceptance function, he determined the probability of a vehicle's accepting a certain gap to determine the needed gap for making a left

turn. Unfortunately, the model is designed to abort left turns when those turns cause a jammed flow situation (37).

COMPARISON OF TWLTLS WITH OTHER MEDIAN TREATMENTS

Some literature concentrates on comparing TWLTLs with other median treatments (raised or depressed medians, typically). While some of this literature is presented as results of research, much of it is presented in the form of survey results or personal comments.

Survey Results

The surveys summarized here were surveys of public highway engineers by various technical committees. One survey (38) addresses TWLTL experience directly. Questions that were asked included the amount of experience respondants had with TWLTLs, how many miles of TWLTL were in their jurisdiction and more subjective questions concerning observed operating characteristics. The survey also asked if respondants felt TWLTLs statistically improve arterial operation by reducing or accident rates, improved travel speeds, etc.

Another survey was directed toward engineers having experience with TWLTLs and median acceleration lanes (MALs). MALs are used at T-intersections, typically, in order to provide acceleration room for vehicles turning left from the stem of the T. TWLTLs were favored by most

respondants. The concluding comments recognized that "more research is needed to develop guidelines [for] the appropriate . . . median treatment for site specific roadway and traffic conditions" (39).

Design Guidelines

The new AASHTO "Green Book" (40) gives generalized comments on techniques to provide for excessive left-turning volumes. Summing up, the Green Book states that any type of access control should meet four basic criteria: it should 1) limit the number of conflict points, 2) separate basic conflict areas, 3) reduce maximum deceleration requirements, and 4) remove turning vehicles from through lanes.

The Federal Highway Administration recommends TWLTLs as a design alternative which provides safe deceleration and storage areas for left-turning vehicles. TWLTLs are also recommended because midblock locations on arterials have the potential to limit capacity because of excessive left-turning movements. In addition, TWLTLs contribute to the flexibility of a road, since they can also be used as HOV or reversible flow lanes during peak periods. Other median treatments are presented as being advantageous for the reduction of accidents due to vehicle cross-overs and quick stops by left-turning vehicles. Very high concentrations of vehicles at median openings could contribute to degradation of flow, however (41).

ITE's Guidelines discuss TWLTLs and medians separately. TWLTLs are recommended as alternatives for situations withhigh commercial development and narrow right-of-way. The "preferred" median treatment, however, involves an unspecified type of median with provisions for left turns at intervals. The provisions for left turns may be as conventional as a left-turn lane cut into the median or it could be an indirect left turn (jughandle or cloverleaf) (42).

One of the earlier studies on median treatments (43) ignores the subject of TWLTLs completely. The theory proposed by this study is that access to abutting land uses should be restricted as much as possible with left turns permitted at median openings or at intersections. Sufficient right-of-way was recognized as being necessary for adequate U-turning radius.

OTHER RELEVANT LITERATURE

While the following literature is not directly related to TWLTLs, it presents concepts essential to the determination of the characteristics of left-turning vehicles

Left-Turn Lane Literature

Kenneth Agent's left-turn lane warrants (44) were based on delay (maximum of 30 seconds per vehicle), load factor (0.3 is critical), accidents (maximum of four per year at

unsignalized intersections, or five per year at signalized intersections) and traffic conflicts. NETSIM was used to develop relationships between left-turn percentage, total volume and cycle split.

The SOAP 84 User's Manual provides a model for the calculation of the capacity of unprotected left-turn intervals at signalized intersections (45). This model could be used to determine the capacity of an unprotected mid-block left-turn interval since similar conditions exist at mid-block with the exception of the traffic signal.

Capacity Literature

The capacity-oriented literature reviewed outlines relatively simple methods for determining the capacity of a road. Dudek (46), in an effort to determine freeway capacity where one or two lanes was closed for construction, used 30 minute counts. Apparently, these counts were performed during peak periods since the capacity of the facility was determined from the highest of these counts.

Another report (47) used similar techniques but used 2 minute counts to better capture the peaking characteristics of freeway flow. Histograms were plotted of the flow rate versus the time of day. The capacity was then determined by looking at the highest flow rate (which occured during the morning peak). The authors complained that the term "capacity" was in need of

clarification, since they felt that capacity needed to be maintained for a specific length of time.

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Appendix B

Review of Literature

REVIEW OF LITERATURE

Project No. E-20-G03 (R6144-0A0)
Criteria for Two-Way Left-Turn Lanes
Versus Other Median Treatments
Task Order No. 6 Under BOA No. 90 Dated
1/9/84

Prepared by Georgia Tech, Civil Engineering for Georgia DOT
August, 1986

Over the thirty years since the first Two-Way Left-Turn Lane (TWLTL) was installed considerable research on the TWLTL's operating characteristics has been done. Around the time of the installation of the first TWLTL, highway engineers had been removing bi-directional passing lanes because of very high head-on collision rates. Consequently, many engineers were reluctant to use another road configuration involving a lane used by vehicles traveling in both directions.

Because of the accident problems experienced by the bi-directional passing lanes, TWLTLs were opposed by traffic engineers who felt that TWLTLs would have similarly high head-on accident rates. As a consequence, early TWLTL studies concentrated on two major points: improper (i.e., potentially dangerous) use of TWLTL's and the comparison of before-TWLTL and after-TWLTL accident rates. Typically, head-on collision rates were studied to see if they increased after TWLTL installation. Even though an early study on TWLTL operation showed that head-on collisions were an uncommon occurrence and of little concern (1), later studies included head-on collisions as part of their accident analysis.

During the late 1960s the increase in commercial strip

development in the form of fast-food restaurants and shopping centers produced a need for some traffic engineering technique which could handle the increased midblock left-turn volume. The TWLTL was seen as an safe and effective way to handle midblock left turns. As TWLTL use increased, so did the desire to learn more about its operating characteristics. Two projects conducted during the mid-1970's addressed TWLTL operating characteristics.

Nemeth's research at the Ohio State University (2) specifically focused on the operating characteristics of TWLTLs, and also included a literature review summarizing previous TWLTL research. The other major research concerning median treatments was performed by Glennon for the FHWA in 1975 (3). Glennon's results allowed the user to determine the optimum median treatment, given the ADT and level of roadside development of a certain road. would determine the optimum median treatment.

Since the mid-1970's TWLTLs have continued to be the focus of much research. In 1979, Parker used regression equations to determine the best type of median treatment based on ADT and accident rates (4). Other recent research has used computer simulation in an effort to simulate arterial operation (5, 6, 7).

In an effort to organize a TWLTL and median treatment based literature review, the literature will be grouped as follows: 1) Accident Research, 2) Operational

Characteristics, 3) Volume/Capacity Research, 4) Computer Simulation, 5) Comparison of TWLTLs with Other Median Treatments, and 6) Other Relevant Literature.

ACCIDENT RESEARCH

Accident-oriented research forms a large part of the TWLTL body of knowledge for two major reasons: accident reports are easy to find for statistical analysis also, early opponents of TWLTLs used high accident rates as a defense against TWLTL use. Accident research usually focused on one of two basic methodologies: comparison of accident rates before and after the installation of a TWLTL, or determination of TWLTL effectiveness based on benefit-cost ratios.

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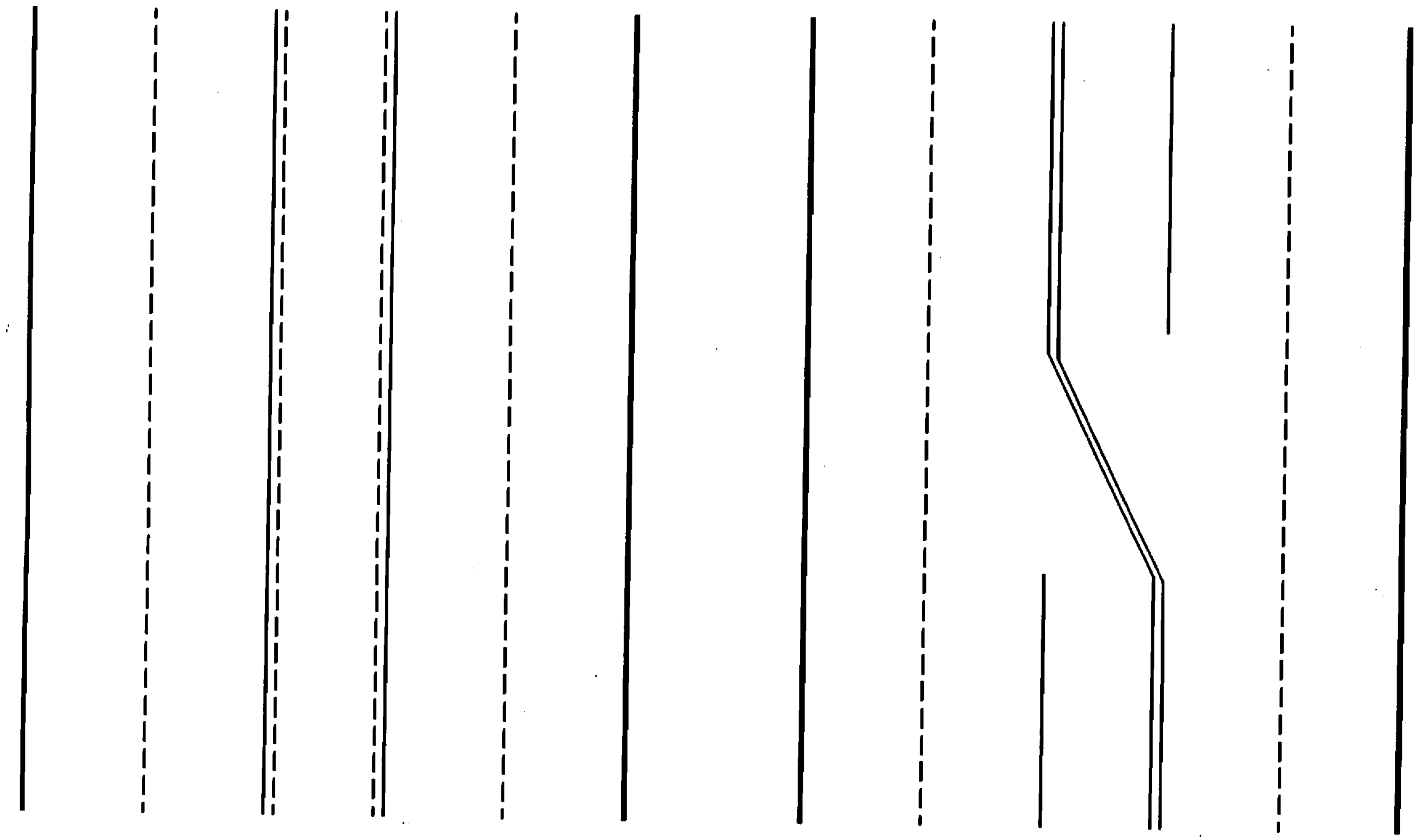

FIGURE 1 - DIFFERENT TYPES OF LEFT-TURN LANES

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Accident-oriented research using benefit-cost ratios as criteria were often presented as an extension of the accident-rate reduction research so as to justify a certain median treatment on the basis of the benefit-cost ratio of the improvement. As it is with any accident-oriented research, the major difficulty associated with benefit-cost ratios is the difficulty of estimating the cost of the "typical" accident. It is not terribly

difficult to determine the average cost of a property damage only accident; placing a "price on someone's head" is an entirely different matter. The difficulty in determining human worth is a good reason why much accident-oriented research stops after it states the potential reduction in accidents associated with a given median treatment; it is left to the engineer using the results to translate that reduction into a "dollars and cents" quantity.

Glennon and Harwood's research (16) adopted this method in analyzing the choice of median treatments. The final results took into consideration ADT and the level of development along the arterial and presented the results in a tabulated form. Their results showed that a TWLTL was preferred even for high levels of ADT and roadside development. This result implies no limit on the traffic volumes for efficient TWLTL operation.

Several potential problems exist with Glennon and Harwood's techniques and the authors address them. The benefit data was based on vehicular delay and accident reduction data, and the accident reduction data was based on regression equations, which are not necessarily accurate predictors of real-world activity. Also of concern is that the cost information was based on 1974 data and must be adjusted to compensate for inflation.

Benefit-cost ratios typically favor TWLTLs since the initial construction cost is low with respect to other

median treatments (raised or depressed medians, for instance). TWLTLs can be constructed on relatively narrow right-of-way. In some situations, TWLTLs can be created by restriping a 2- or 4-lane highway with little or no widening.

Thakkar (17) also used a benefit-cost analysis to determine that TWLTLs were economic and safe alternatives on highly-developed arterials. The low construction cost of a TWLTL again helped to make it a favorable median treatment.

OPERATIONAL CHARACTERISTICS

In an effort to determine the effect of TWLTLs on the "typical" vehicle traveling on an arterial, research has also concentrated on the operational characteristics of TWLTLs. Nemeth was one of the major researchers in this area. He analyzed different roadway sections, using before and after TWLTL installation running times as the TWLTL's measures of effectiveness (18). Nemeth also analyzed TWLTL effectiveness in terms of weavings and braking (mentioned above). In two out of three cases TWLTLs were found to increase running speeds when compared with the "before" case (prior to TWLTL installation). Only in the case where a four-lane highway was restriped as a three-lane highway did the quality of flow suffer.

Harwood and St. John's research on operational improvements on two-lane highways (19) also dealt with the effectiveness of TWLTLs installed on 2-lane roads. The results of their research were presented in the form of a regression equation used to predict the delay per left-turning vehicle as a function of the opposing volume. While this seems a logical relationship, the R^2 for his equation was only 0.32, and a raw data plot showed the presence of two highly influential points at large volumes.

VOLUME/CAPACITY LITERATURE

A large portion of available literature addresses, in one form or another, the relationship between volume and median treatment. In this aspect of median treatment choice, much of the literature is informal in nature, with the author stating certain volume ranges which have been observed to operate adequately. The remainder of the applicable literature is more academic in nature, involving some sort of study which attempted to relate volumes and operating characteristics.

The concept of a capacity on a road with a TWLTL is expressed casually in much of the literature. Fisher (20) observed "satisfactory at best" operation of seven-lane facilities with ADT around 40,000. This statement concurs favorably with Lebel's statement (21) that a

five-lane (four through lanes plus a TWLTL) section near Grand Rapids, with ADT around 40,000 is not operating as well as it did at lower volume levels. The preferred treatment for the Grand Rapids example is a "boulevard-type design," with the through lanes separated by a raised, curbed median and left-turn pockets at intervals. The actual reconstruction of the Grand Rapids arterial also included reorganization of access driveways and roadside signs in an effort to reduce driver confusion (22).

Although Glennon's work (23) was mainly accident oriented, his TWLTL "warrant" was for ADT between 10,000 and 20,000. Similarly, McCormick's accident work (24) was done on highways with ADT's of around 20,000. In addressing accident experience on seven-lane roads, Parker (25) mentioned that the accident rates on seven-lane roads, with ADT around 20,000, are not significantly higher than those on five-lane roads.

Nemeth's work (26) during the mid-1970s included a literature search which highlighted several comments concerning the optimum volume range for TWLTL-equipped roads. TWLTLs use was documented over a range of ADT extending from 8,000 to 31,000. At all volume levels TWLTL's were found to reduce the accident rates.

Nemeth cites a literature search by the Georgia Section of the ITE which recommended TWLTL use on five-lane roads with ADTs between 10,000 and 25,000. Three-lane sections

were recommended for ADTs below 10,000. This search also concluded that the benefits of a TWLTL (lower accident rates, lower left-turn vehicular delay, lower through vehicle delay) become questionable as the volumes approach capacity due to the lack of gaps in opposing traffic needed to make left turns (27).

The state of Washington uses TWLTLs on multilane roads with ADT between 10,000 and 25,000 and on two-lane roads between 5,000 and 12,500 (28). Their upper limit of 25,000 ADT is echoed by Thompson (29) for a five-lane road. Thompson goes on to state that 40,000 ADT exceeds the practical capacity of a seven-lane road, which he concludes on the basis of observing a seven-lane road with 40,000 ADT in Grand Rapids.

Sawhill and Hall state that "traffic volumes as such are not always found to be a warrant, but volumes approaching roadway capacities in either direction may be a reason for not installing the TWLTL, more important would be the observations of time gaps or sufficient length for left turn movements to be accomplished." (30).

Both the old and new Capacity Manuals address the capacity characteristics of roads with various median treatments. One states that because a raised median reduces the "friction" between opposing directions of traffic, a road with a raised median will have a higher capacity than a five-lane road (31). While the new Capacity Manual (32) recognizes that midblock congestion

can be the limiting capacity factor, it states no method for midblock capacity determination. Elsewhere, the new manual states that a road with a TWLTL will operate somewhere inbetween an undivided and a divided road. The "Adjustment Factor for Type of Multilane Highway and Development Environment" is an attempt to quantify the effects of roadside development and median treatments in the calculation of highway capacity. This factor is determined subjectively and has no numerical guidelines. Harwood's recent research on median alternatives (33) states the preferred condition for TWLTLs: low to moderate through volumes, high left-turn volumes, high driveway densities and high rear-end and right-angle accident rates. He states that delay reduction (compared with no TWLTL) is modest at low volume levels and large at large flow rates. He also states that little work has been done to establish volume ranges for the installation of TWLTLs.

COMPUTER SIMULATION

Since the mid-1970's computer simulation of arterial operation has been a popular method to model operating characteristics under a variety of conditions. Heikal developed the ARTSIM program (34) to model arterial flow at varying levels of through volume, left-turn volume, and roadside development. The level-of-service concept

propsed by Heikal is based on the friction between left-turning vehicles and through vehicles and is measured in the average number of stops per vehicle. ARTSIM was developed to compare the quality of arterial flow with and without a TWLTL, and it could be used to model TWLTLs under a variety of circumstances as well as boulevard-type arterial design.

Similarly, McCoy (35) used the General Purpose Simulation System (GPSS) language to simulate the operation of a three-lane facility. GPSS allows the user to specify different volumes and driveway densities. McCoy used the reduction in stops and delay as his measures of effectiveness.

The NETSIM computer program was proposed for the determination of the quality of urban arterial flow (36). It involved considerable data collection with respect to the geometrics of the arterial. Careful data collection would ultimately provide a realistic computer model. Although specific references to TWLTLs were not made, NETSIM could be easily adapted to research aimed at quantifying the operating characteristics of urban arterials with TWLTLs.

McCoy's latest simulation work, TWLTL-SIM, written with GPSS was written to simulate a 5-lane section with TWLTL. Using Gerlough and Wagner's gap acceptance function, he determined the probability of a vehicle's accepting a certain gap to determine the needed gap for making a left

turn. Unfortunately, the model is designed to abort left turns when those turns cause a jammed flow situation (37).

COMPARISON OF TWLTLS WITH OTHER MEDIAN TREATMENTS

Some literature concentrates on comparing TWLTLs with other median treatments (raised or depressed medians, typically). While some of this literature is presented as results of research, much of it is presented in the form of survey results or personal comments.

Survey Results

The surveys summarized here were surveys of public highway engineers by various technical committees. One survey (38) addresses TWLTL experience directly. Questions that were asked included the amount of experience respondants had with TWLTLs, how many miles of TWLTL were in their jurisdiction and more subjective questions concerning observed operating characteristics. The survey also asked if respondants felt TWLTLs statistically improve arterial operation by reducing or accident rates, improved travel speeds, etc.

Another survey was directed toward engineers having experience with TWLTLs and median acceleration lanes (MALs). MALs are used at T-intersections, typically, in order to provide acceleration room for vehicles turning left from the stem of the T. TWLTLs were favored by most

respondants. The concluding comments recognized that "more research is needed to develop guidelines [for] the appropriate . . . median treatment for site specific roadway and traffic conditions" (39).

Design Guidelines

The new AASHTO "Green Book" (40) gives generalized comments on techniques to provide for excessive left-turning volumes. Summing up, the Green Book states that any type of access control should meet four basic criteria: it should 1) limit the number of conflict points, 2) separate basic conflict areas, 3) reduce maximum deceleration requirements, and 4) remove turning vehicles from through lanes.

The Federal Highway Administration recommends TWLTLs as a design alternative which provides safe deceleration and storage areas for left-turning vehicles. TWLTLs are also recommended because midblock locations on arterials have the potential to limit capacity because of excessive left-turning movements. In addition, TWLTLs contribute to the flexibility of a road, since they can also be used as HOV or reversible flow lanes during peak periods. Other median treatments are presented as being advantageous for the reduction of accidents due to vehicle cross-overs and quick stops by left-turning vehicles. Very high concentrations of vehicles at median openings could contribute to degradation of flow, however (41).

ITE's Guidelines discuss TWLTLs and medians separately. TWLTLs are recommended as alternatives for situations withhigh commercial development and narrow right-of-way. The "preferred" median treatment, however, involves an unspecified type of median with provisions for left turns at intervals. The provisions for left turns may be as conventional as a left-turn lane cut into the median or it could be an indirect left turn (jughandle or cloverleaf) (42).

One of the earlier studies on median treatments (43) ignores the subject of TWLTLs completely. The theory proposed by this study is that access to abutting land uses should be restricted as much as possible with left turns permitted at median openings or at intersections. Sufficient right-of-way was recognized as being necessary for adequate U-turning radius.

OTHER RELEVANT LITERATURE

While the following literature is not directly related to TWLTLs, it presents concepts essential to the determination of the characteristics of left-turning vehicles

Left-Turn Lane Literature

Kenneth Agent's left-turn lane warrants (44) were based on delay (maximum of 30 seconds per vehicle), load factor (0.3 is critical), accidents (maximum of four per year at

unsignalized intersections, or five per year at signalized intersections) and traffic conflicts. NETSIM was used to develop relationships between left-turn percentage, total volume and cycle split.

The SOAP 84 User's Manual provides a model for the calculation of the capacity of unprotected left-turn intervals at signalized intersections (45). This model could be used to determine the capacity of an unprotected mid-block left-turn interval since similar conditions exist at mid-block with the exception of the traffic signal.

Capacity Literature

The capacity-oriented literature reviewed outlines relatively simple methods for determining the capacity of a road. Dudek (46), in an effort to determine freeway capacity where one or two lanes was closed for construction, used 30 minute counts. Apparently, these counts were performed during peak periods since the capacity of the facility was determined from the highest of these counts.

Another report (47) used similar techniques but used 2 minute counts to better capture the peaking characteristics of freeway flow. Histograms were plotted of the flow rate versus the time of day. The capacity was then determined by looking at the highest flow rate (which occured during the morning peak). The authors complained that the term "capacity" was in need of

clarification, since they felt that capacity needed to be maintained for a specific length of time.

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Appendix C

Annotated Bibliography

ANNOTATED BIBLIOGRAPHY

Project No. E-20-G03 (R6144-OAO)
Criteria for Two-Way Left-Turn Lanes
Versus Other Median Treatments
Task Order No. 6 Under BOA No. 90 Dated 11/9/84
Prepared by Georgia Tech, Civil Engineering for Georgia DOT
August, 1986

Agent, Kenneth R., "Warrants For Left-Turn Lanes," Transportation Quarterly, Vol. 37, No. 1, January 1983, Westport, Connecticut, pp. 99-114.

The purpose of this report was to develop numerical criteria for the installation of a left-turn lane. Agent cites the fact that few states use numerical warrants for left-turn lane installation. Most states do have some form of guidelines, however, usually based on accidents, volume or delay. The paper presents warrants based on these three parameters.

Agent chooses 30 seconds of delay as excessive for a signalized intersection. 0.3 is the critical load factor chosen for volume warrants, and four (unsignalized) or five (signalized) left-turn accidents in one year is also a warrant for a left-turn lane. These criteria were analyzed using NETSIM, and relationships between left-turn percentage, total main street volume, and cycle split were derived to determine the volume warrant. Delay per vehicle, percent left turns and opposing volume were used to determine the delay warrant criteria. A warrant is also provided for traffic conflicts: an average of 30 or more total left-turn related conflicts or 6 or more opposing left-turn conflicts in a 3-hour study period during peak conditions.

American Association of State Highway and Transportation Officials, A Policy on Geometric Design of Highways and Streets, 1984, Washington, p. 109-110.

Information given by this document is general, directing the reader to other documents and providing general guidelines concerning access control, with the major emphasis being safety improvement of existing highways. The purpose of access control is to reduce the interference with through traffic by other vehicles or pedestrians entering, leaving, and crossing the highway. On streets or highways where there is no control of access and roadside businesses develop, interference from the roadside can become a major factor in reducing the capacity, increasing the accident potential and eroding the mobility function that the facility was designed to provide. If access points are numerous and entering and exiting volumes are heavy, the capacity and safety of the facility are reduced. Any form of access control should meet these four major criteria: limit the number of conflict points, separate basic conflict areas, reduce maximum deceleration requirements and remove turning vehicles from the through lanes.

Dale, Charles W., "Procedure for Evaluating Traffic Engineering Improvements," ITE Journal, April 1981, pp. 39-46.

This article outlines procedures for evaluating low-capital improvements. Most of the measures of effectiveness are user-oriented, such as user cost, travel time, and fuel consumption. The author suggests that volume data be obtained from local planning organizations, but mentions nothing about determining the capacity of existing highways.

Dudek, Conrad L., and Stephen H. Richards, "Traffic Capacity Through Urban Freeway Work Zones in Texas," Transportation Research Record 869, Washington, 1982, pp. 14-18.

This report dealt with the problem of determining the capacity of a freeway section which had one or more through lanes closed for construction work. The authors determined the capacity of the remaining open lanes by counting cars over a 30-minute period (presumably the peak period), converting that to an equivalent flow rate, and calling that the capacity. It was not stated when these counts were made.

Federal Highway Administration, "Design of Urban Streets," Student Textbook, prepared by JHK & Associates for the United States Department of Transportation, Washington, September, 1977, pp. 6-6, 7-12, 7-14.

Midblock techniques for maximizing capacity are discussed, as "midblock sections may experience significant amounts of traffic interruption, primarily due to access/egress movements." TWLTLs provide safe deceleration and storage areas for vehicles turning left, reducing delay and disturbances to the overall traffic flow. they can be used as a reversible lane or an HOV lane during peak periods.

Nemeth's report of July, 1976 is referenced. The 1972 Michigan study of four arterials converted to TWLTL (Two-Way Left-Turn Lane) operation is quoted, including the 33 percent reduction in total accidents. However, high speeds combined with rolling terrain is hazardous. Also, if the number of movements made in the lane becomes too large there will be an increase in accidents or near accidents.

The textbook briefly discusses the advantages and disadvantages of physical (raised) medians of various widths, and three kinds of painted medians. Raised medians at least four feet wide can provide pedestrian refuge, and a pushbutton can be installed on the median to increase the efficiency of main-street flow. They can reduce accidents due to vehicle cross-overs and sudden stops by left-turning vehicles. However, turns from or to cross streets may become overconcentrarted at median openings and U-turns may become a problem at these points.

Fisher, John E., letter to Mark R. Norman of May 14, 1985, city of Los Angeles traffic engineer.

Mr. Fisher mentions in his letter that he has extensive experience with seven lane highways, several with ADT in excess of 40,000 vehicles in the Los Angeles area. Most of these highways have right-of-way usually less than 100 feet. He describes the operation on these streets as satisfactory at best. He does not recommend a seven lane section as a standard, preferring a divided section with left-turn bays at intervals.

Georgia Division, Southern Section, Institute of Traffic Engineers, "Report of a Study of Two-Way Left-Turn Lanes".

This report was cited by Nemeth, who quoted the Georgia Division as recommending TWLTL use on five-lane roads with ADTs between 10,000 and 25,000. Three-lane sections were recommended for ADTs below 10,000. This paper also concluded that the benefits of a TWLTL (lower accident rates, lower left-turn vehicular delay, lower through-vehicle delay) became questionable as the volumes approach capacity due to the lack of gaps in opposing traffic needed to make left turns.

Glennon, J.C., et. al., "Evaluation of Techniques for the Control of Direct Access to Arterial Highways," Report No. FHWA-RD-76-87, Federal Highway Administration, Washington, August, 1975.

Glennon et al. found that the TWLTL is inferior to the raised median where frequent driveways are in combination with high arterial street volumes. A TWLTL is a more effective accident reduction technique at lower levels roadside development and traffic volumes as reflected in the tabulation below:

Level of Roadside Development (driveways per mile)	Highway ADT	Estimated Annual Accident Reduction Per Mile: Raised Median	Estimated Annual Accident Reduction Per Mile: Continuous TWLTL
Low (<30)	Low (<5,000)	2.2	4.4
High (>60)	High (>15,000)	31.2	28.6

Glennon suggested that a TWLTL be employed only where conventional raised or flush medians are not practical. He recommended that a TWLTL be warranted when ADT reaches 10,000 to 20,000 vpd, level of development exceeds 60 driveways per mile, fewer than 10 high-volume driveways per mile, speeds >30 mph. Also, left-turning driveway maneuvers per mile should total at least 20% of the traffic volume during peak periods.

City of Grand Rapids, Michigan, The 28th Street Corridor Project, 1981.

This report was written to suggest a solution to congestion because of high mid-block left turns and the associated accident rate. 28th Street is a five-lane facility with 40-50,000 ADT. Recommended improvements included raised medians with left turn pockets at intervals and consolidation of signs to abutting businesses. Also recommended were aesthetic improvements to improve the motorists' ability to take in the businesses abutting the street.

Harwood, Douglas W., "Multilane Design Alternatives for Improving Suburban Highways", NCHRP Report 282, Transportation Research Board, Washington, D.C., 1986, pp. 27-59.

Like Parker (1979), Harwood developed regression equations to estimate accidents. This work seems to be the most recent of this type. Harwood's comparison of different types of arterials used 8 independent variables: ADT, truck percentage, type of development, estimated level of left-turn demand, shoulder width, speed, driveways per mile, and unsignalized intersections per mile. A statistical analysis of the difference in accident rates between different arterial designs was conducted. Analyses of covariance for nonintersection and unsignalized intersection accident rates was done in an effort to determine factors relevant to accident rates. Unfortunately, the groupings for ADT extended up to 20,000, with one category for ADTs "over 20,000" to cover high-volume arterials. Harwood's conclusions relating to accidents can be summarized only by reprinting five tables:

Table 1. Average accident rates for nonintersection accidents on suburban arterial highways.

BASIC ACCIDENT RATES
(accidents per million vehicle-miles)

Type of Development	Design Alternative 2U	3T	4U	4D	5T
Commercial	2.39	1.56	2.85	2.90	2.69
Residential	1.88	1.64	0.97	1.39	1.39

ADJUSTMENT FACTORS

	Under 30	30-60	Over 60
Driveways per mile	-0.41	-0.03	+0.35

	Under 5%	5-10%	Over 10%
Truck percentage	+0.18	-0.07	-0.33

Note: Accident rates should be decreased by 5% for highway sections with full shoulders and increased by 5% for highway sections with no shoulders.

Table 2. Average accident rates for unsignalized intersection accidents on suburban arterial highways.

BASIC ACCIDENT RATES
(accidents per million vehicle-miles)

Type of Development	Design Alternative 2U	3T	4U	4D	5T
Commercial	2.11	2.43	4.77	4.71	3.11
Residential	2.88	1.91	3.03	2.71	1.85

ADJUSTMENT FACTORS

	Under 5	5-10	Over 10
Intersections per mile	-0.99	+0.28	+1.55

	Under 5%	5-10%	Over 10%
Truck percentage	+0.22	-0.08	-0.38

Table 3. Total accident rates for suburban arterial highways (including nonintersection and unsignalized intersection accidents).

BASIC ACCIDENT RATES
(accidents per million vehicle-miles)

Type of Development	Design Alternative 2U	3T	4U	4D	5T
Commercial	4.50	3.99	7.62	7.61	5.80
Residential	4.76	3.55	4.00	4.10	3.24

ADJUSTMENT FACTORS

	Under 30	30-60	Over 60
Driveways per mile	-0.41	-0.03	+0.35
	Under 5%	5-10%	Over 10%
Intersections per mile	-0.99	+0.28	+1.55
	Under 5%	5-10%	Over 10%
Truck percentage	+0.40	-0.15	-0.71

Table 4. Accident severity distribution for suburban arterial highways.

Design Alternative	Percent of Accidents Involving a Fatality or Injury: Nonintersection Accidents, Commercial	Nonintersection Accidents, Residential	Unsignalized Intersection Accidents, Commercial	Unsignalized Intersection Accidents, Residential
2U	38.4	43.6	39.0	32.9
3T	29.9	43.6	32.1	32.9
4U	38.4	38.8	32.1	32.9
4D	33.7	43.6	26.9	45.1
5T	33.7	38.8	32.1	26.6

Table 5. Distribution of accident types susceptible to correction by multilane design alternatives.

Design Alternative	Percent of Accidents Susceptible to Correction[a]: Nonintersection Accidents, Commercial	Nonintersection Accidents, Residential	Unsignalized Intersection Accidents, Commercial	Unsignalized Intersection Accidents, Residential
2U	50.5	44.3	55.9	50.5
3T	45.0	49.4	65.2	56.7
4U	45.8	51.6	65.0	63.5
4D	58.6	43.2	55.3	42.4
5T	50.5	60.0	44.6	55.0

[a] Head-on, rear-end, and angle accidents.

Harwood collected no delay data, but used the simulation model TWLTL-SIM to estimate stops and delay on two-lane and four-lane suburban arterials both with and without TWLTLs. He used the same model to estimate the reduction in delay that results from installing a raised median on a four-lane undivided arterial. The results of the operational comparison between four-lane undivided and four-lane divided sections were compared with the effectiveness of five-lane TWLTL sections. Two major conclusions were drawn. First, at flow rates of 900 vph and below, median dividers generally result in an increase in delay. However, at flow rates of 1,100 vph and above, the installation of a median divider on an undivided street reduces delay, even for minimal levels of left-turn demand. These results suggest that the breakpoint where a median divider begins to provide operational benefits is a flow rate of approximately 1,000 vph in each direction of travel. Second, the 5-lane TWLTL design alternative is preferable to both the 4-lane undivided and the 4-lane divided design alternatives for all levels of flow rate, left-turn demand, and driveway density. "This result provides strong evidence that, strictly from an operational standpoint, the use of a TWLTL is a highly desirable alternative in a wide variety of design situations."

Harwood, Douglas W., and John C. Glennon, "Selection of Median Treatments for Existing Arterial Highways," Transportation Research Record 681, Transportation Research Board, Washington, 1978, pp 70-77.

This report looks at five different types of median treatments, the TWLTL, the continuous left-turn lane, the alternating left-turn lane, the raised median divider and the median barrier. Each alternative was analyzed to determine which one would reduce accidents and delay the most.

Regression equations were used to project the accidents on facilities with certain types of median, with each median type analyzed at three levels of ADT and development. Benefit-cost ratios were calculated using the delay and accident reduction data (benefits) and the cost of improving a road to have a certain median treatment (costs) for three different levels of construction.

Results were then tabulated based on these benefit-cost ratios. The final result was a table which allowed the user to determine the preferential median treatment by entering with the level of development and the ADT of the arterial. Caution is advised by the author, since the data used to arrive at the benefit-cost ratios involves construction costs at the time of writing and numbers of accidents based on regression equations, which do not always accurately reflect the actual relationship between the desired variables. Their table of benefit-cost ratios indicate that a TWLTL is preferred even for high ADT and high levels of roadside development. That is, there is no indication that a TWLTL ceases to enjoy its well-known benefits once a certain level of activity is reached.

<u>Harwood</u>, Douglas W., and C. J. Hoban, <u>Low-Cost Operational and Safety Improvements for Two-Lane Roads: Informational Guide</u>, Federal Highway Administration, Washington, D.C., 1986, pp 66-67.

This report is a review of existing literature. The authors review previous studies showing that the installation of a TWLTL on a 2-lane road reduces delay, particularly at higher-volume urban-fringe sites. Regarding accidents, the authors quote Harwood and Glennon, 1978, who reported that TWLTLs reduce accident rates by about 35 percent, when installed at urban and suburban sites, primarily on multilane highways. Comparable accident reduction effectiveness was found by Harwood and St. John (1986) for installation of TWLTLs on 2-lane highways in urban fringe areas. In rural areas the number of accidents at candidate TWLTLs on 2-lane highways is small, but TWLTLs can reduce these accidents by up to 85 percent.

<u>Harwood</u>, Douglas W., and A. D. St. John, <u>Passing Lanes and Other Operational Improvements on Two-Lane Highways,</u> FHWA/RD-85/028, Washington, D.C., 1985, pp. 99-100.

The authors developed a regression equation to predict the potential delay reduction from installing TWLTLs on 2-lane highways. There were only two data points at high volumes, so the model had little statistical significance.

Heikal, Aly S., and Zoltan Nemeth, "Measure of Potential Benefits from Two-Way Left-Turn Lanes, ITE Journal, June 1985, pp. 22-24.

The authors propose, and adopt for their research, a level-of-service concept by which the quality of mid-block traffic flow is measured by the friction created by mid-block left turns. The average number of stops per vehicle in the inside lane is taken as a measure of conflict between midblock left turns and through traffic. The authors applied this concept only to the inside lanes of four-lane arterials, and used the number of stops only to measure the potential for improvement in through-traffic flow by the installation of TWLTLs. However, the variable could just as well be used in studies of existing TWLTLs to determine the level of left-turning volume at which the TWLTL is no longer to function properly. The authors believe, based on professional judgment, that more than 0.3 stops per vehicle in the inside lane, over the length of a typical city block, indicates a definite need for improvement.

Highway Research Board, Highway Capacity Manual - Special Report 87, Washington, D.C., 1965.

The old Capacity Manual states that with respect to TWLTLs compared with divided sections "Logically, however, because lane capacity is reduced by side interference, among other things, and the raised median will eliminate the side interference on the left and reduce it on the right, the capacity of a divided roadway with protected left-turn lanes will exceed that of a five-lane facility."

Hoffman, M.R., "Two-Way Left-Turn Lanes Work!" in Traffic Engineering, August, 1974, pp. 24-27.

Studies of four Michigan arterials showed that, where no median was previously provided, the installation of continuous TWLTLs reduced total accidents by about 33 percent, with reductions of 45 and 62 percent for head-on and rear-end type accidents, respectively. Mr. Hoffman mentions the limitation of the TWLTL when left-turn volume reaches the capacity of the TWLTL. When this occurs, the facility breaks down and tends to operate more like a typical four lane highway. He goes on to mention that careful driveway planning (working to ensure that driveways, where possible, are positioned opposite other driveways) contributes to the successful operation of a road with a TWLTL. If driveways are positioned such that left-turning traffic interlocks, the efficiency of the facility drops very quickly. He also supports the planning and construction of "service drives" at large shopping centers which serve to channel the traffic to specific exit points in an effort to control access better.

Hurdle, V.F., and P.K. Datta, "Speeds and Flows on an Urban Freeway: Some Measurements and a Hypothesis," Transportation

Research Record 905, Washington, 1983, pp. 130-131.

This report was written to prove the hypothesis that the speed of an expressway may not depend on the flow rate as much as it depends on whether or not the flow is a capacity flow discharged from an upstream queue.

To prove this, the authors first determined the capacity of their subject freeway by performing 2-minute counts during the peak periods of three days, converting these to equivalent flow rates and then graphing the flow rates versus time.

These counts were done in the morning, between 6:30 and 9:00, under the assumption that capacity flow would be achieved somewhere during that interval. By observing the histograms, the authors determined that capacity flow was reached between 7:00 and 8:30. They then averaged the flow rates over this 1-1/2 hour period and found the average to be 1984 pcphpl. Although the authors felt this could be the capacity, they were of the opinion that the term "capacity" needed clarifying in terms of how long a time the capacity flow is maintained.

<u>Institute</u> of Transportation Engineers Committee 4A-2, <u>Report on the Recommended State of the Art Practice for the Design and Use of the Two-Way Left Turn Lane</u>, Institute of Transportation Engineers, Washington, 1978.

This report addresses two issues relevant to median design, especially TWLTLs: 1) the experience of state, county, and city traffic engineers with TWLTLs, and 2) general warrants for the use of TWLTLs.

The experience part of the report was summarized from the results of a survey sent to traffic engineers. The range of questions covered the type and length of experience engineers had with TWLTLs, how they were marked, what happened to the accident rate after installation, and what factors were used to determine if the installation of a TWLTL is warranted.

The warrant for a TWLTL, according to this report, is strictly based on ADT and type of use, although the report acknowledges that left turning volumes are also important when determining whether or not to install one.

<u>Institute</u> of Transportation Engineers Committee 5-5, <u>Guidelines for Urban Major Street Design</u>, Institute of transportation Engineers, Washington, 1979, pp. 7-1-8-10.

Section 7 of the Guidelines addresses median design, which "should be considered for all major urban streets of four or more lanes." Median types are discussed generally and the TWLTL is suggested as an alternative when high commercial development and inadequate right-of-way exists for wide medians with left-turn pockets.

Section 8 discusses TWLTLs and their applications in general terms. Because unrestricted access is so typical or major routes in urban and suburban areas, it should represent a basic design alternative. The general recommendations are that if faced with narrow right-of-way and high turning maneuvers and/or pressure from businesses desiring access to the highway, a TWLTL is the best alternative. If these problems do not exist, a wide median with left-turn pockets at intervals is preferred. The indirect left turn (like a jughandle) is also discussed and advocated as a possible solution. The section mentions that some way must be provided to serve both the through driver and the driver desiring to access abutting property, and that when parallel roads or service roads acting as frontage roads do not exist, a TWLTL is the best solution.

Also mentioned is the fact that there are two basic types of TWLTLs. One is differentiated by the fact that the TWLTL is carried through all intersections with no change in markings for the left-turn lane at major intersections. The other type involves terminating the TWLTL in order to provide a left-turn lane at major intersections.

<u>Institute</u> of Transportation Engineers Technical Committee 5B-4, "Effectiveness of Median Storage and Acceleration Lanes for Left-Turning Vehicles," <u>ITE</u> <u>Journal</u>, March, 1985, Washington, p. 61.

This article presents the results of a survey of Canadian and American municipalities concerning their experience with median treatments. Two major types of median treatments were considered: median acceleration lanes which separated traffic traveling to or from the minor street from the through lanes, and TWLTLs. The overall opinion was positive towards TWLTLs, with response to median acceleration lanes being mixed. No extensive use guidelines are given, and the paper mentions that "more research is needed to develop guidelines...[for]...the appropriate. . . median treatment for site specific roadway and traffic conditions."

General guidelines are given for TWLTL use. The article states that TWLTLs are best for strip development, should not be used for through traffic, and that TWLTLs must be signed and marked well to reduce indicision and misuse.

<u>JHK</u> & Associates, <u>Design</u> <u>of</u> <u>Urban</u> <u>Streets</u> <u>Student</u> <u>Textbook</u>, U.S. Department of Transportation, Washington, 1977, pp. 6-6.

The initial introduction to TWLTLs states that they are most commonly used on streets with dense adjacent development. It goes on to say that TWLTL operation has proven to be safe and that they result in less delay and disturbance to the overall traffic flow. In the portion of the textbook which discusses medians, TWLTLs are mentioned as a good method of access control, and the reader is referred to Nemeth's report for guidelines on the installation and use of TWLTLs. Mention is also made that care must be taken in TWLTL use, since high turning volumes in TWLTLs can contribute to increased accident rates.

Knoblauch, R. L., M. R. Parker, Jr., and J. C. Keegel, Traffic Control for Reversible Flow Two-Way Left-Turn Lanes, Final Report, FHWA-RD-85/009, Federal Highway Administration, Washington, D.C., October, 1984.

The authors suggest replacing the flashing yellow "X" with the flashing doube-yellow arrow symbol.

Lebel, William T., letter to Mark R. Norman of May 10, 1985 and attached in-house report, State of Michigan Department of Transportation, Lansing, Michigan.

Michigan generally uses TWLTLs in situations (2, 4, or 6 through lanes) with high levels of strip development. Lebel recognizes that the effectiveness of TWLTLs is limited at high volumes, since left turns into and out of abutting businesses become difficult. Lebel also mentions that pedestrian crossing placement is limited due to the lack of signal placement flexibility, and that future highway expansion (like to a divided section) is not practical once abutting development is in place because of right-of-way constraints.

Lebel goes on to mention that a five-lane section near Grand Rapids, which has an ADT of 40,000 is not "operat[ing] as favorable as it does at lower levels. In this case there is little doubt in our mind that a boulevard-type design is preferred." He states that a boulevard-type design (through traffic lanes separated by a grassed median with left-turn pockets at major intersections and at intervals between intersections) would allow left turns to be made at these designated crossovers (later referred to as directional median crossovers), where signalization could be provided to control the left turn movements without compromising through capacity. He cites Savage's article in the August, 1974 issue of Traffic Engineering for further descriptions of the directional median crossover concept.

For a situation with ADT in the upper 40,000's and wide right-of-way, he recommends a six-lane section with planned U-turns at signalized intersections.

An attached report mentions that "at capacity, left turn movements become very difficult either onto or off from the facility." It mentions that boulevard-style design is preferred when building a new arterial or widening an existing arterial in an undeveloped area. The report also states that accidents related to left-turning vehicles have been found to decrease when TWLTL's are installed on a facility previously having no provision for mid-block left turns.

Levenson, Herbert S., et. al., "Callahan Tunnel Capacity Management," Transportation Research Record 1005, Washington, 1985, pp. 4-5.

This report addresses the need to equalize the capacity of a tunnel at all points along the tunnel. Prior to the implementation of the measures designed to equalize flow, a capacity analysis of the tunnel was performed. The capacity was determined by looking at other similar tunnels for which maximum observed volumes were known. These volumes were averaged and compared with the capacity as calculated in the Highway Capacity Manual to estimate the capacity of the tunnel.

McCormick, David P., and Eugene M. Wilson, "Comparing Operational Effects of Continuous Two-Way Left Turn Lanes," University of Wyoming, Laramie, no date, pp. 6-7.

This report compares TWLTLs with two other median treatments: no median treatment, and the alternating left-turn lane. They determined effectiveness by a conflict analysis and found the TWLTL to reduce conflicts considerably over either of the two other treatments. The only volume requirements mentioned were ADTs of 10,000 to 20,000. The assumption here is that the number of conflicts are directly proportional to the number of accidents on a highway. Although volumes of the study roadways are given, no mention is made of the effectiveness of any of the median treatments at high or low volumes.

McCoy, Patrick T., et. al., "Operational Effects of Two-Way Left-Turn Lanes on Two-Way Two-Lane Streets," Transportation Research Record 869, Transportation Research Board, Washington, 1982, p. 53.

This report evaluated operational effects of a TWLTL from a computer simulation viewpoint. McCoy used the General Purpose Simulation System (GPSS) language to simulate the operation of a two-lane road with a TWLTL. Different traffic volumes and different driveway densities were used and their effectiveness was measured in terms of reductions of number of stops and reduction of delay.

McCoy, Patrick T., Guidelines for the Use of Two-Way Left-Turn Lanes, Federal Highway Administration, Washington, D.C., 1986, preliminary report.

This is a follow-up simulation study to the one cited above. TWLTL-SIM was written to simulate a 5-lane section with TWLTL. Using Gerlough and Wagner's gap-acceptance function, he determined the probability (of a driver's accepting a certain gap) to determine the needed gap for making a left turn. Unfortunately, the model is designed to abort left turns when those turns cause a jammed flow situation.

<u>McDonald</u>, J.W., "Relation Between Number of Accidents and Traffic Volume at Divided Highway Intersections," Highway Research Bulletin 74, Highway Research Board, Washington, 1953.

This report presents a prediction equation for the expected accident experience of four-way, unsignalized intersections on divided highways.

<u>Mulinazzi</u>, T.H., and H.L. Michael, "Correlation of Design Characteristics and Operational Controls With Accident Rates on Urban Arterials," Joint Highway Research Project, Purdue University and Indiana State Highway Commission, 1967.

This report presents regression equations for accident rates on urban arterials and is used as the basis of the regression data in Glennon's work.

<u>Nemeth</u>, Zoltan A., "Development of Guidelines for the Application of Continuous Two-Way Left-Turn Median Lanes," The Ohio State University, July 1976, pp. 6-9.

This report began with a literature review in order to determine the conditions under which TWLTLs were implimented and how the TWLTLs impacted the quality of flow along the arterial. The traffic volume section mentions several capacity-oriented figures. The range of volumes which were served by a TWLTL were from 8,000 to 31,000 ADT, and it was mentioned that accident reductions were seen at all ranges of volumes.

The Georgia Division of the ITE concluded, from their literature search, that TWLTLs are best used on five-lane facilities with volumes between 10,000 and 25,000 ADT. Below 10,000, three-lane facilities can be used successfully. The Georgia ITE report also mentioned "that as traffic volumes approach capacity, the gaps in opposing traffic available for left turns are very limited, so that the value of the TWLTL in reducing congestion then becomes questionable."

Sawhill and Hall of the University of Washington also stated that "Traffic volumes as such are not always found to be a warrant, but volumes approaching roadway capacities in either direction may be a reason for not installing the TWLTL; more important would be the observation of time gaps of sufficient length for left turn movements to be accomplished." The Washington State Department of Highways uses TWLTLs only on facilities with ADTs between 10,000 and 25,000 for multilane facilities and between 5,000 and 12,500 for two-lane facilities. The report mentions that more investigation might be justified on the effect of the TWLTL at the limits of the ADT range before conclusive results can be stated.

The report presents the results of three before-and-after studies done on Ohio arterials. In two out of the three situations, traffic flow conditions improved in the after case, with the one degredation occuring when a road used as a four-lane highway was re-striped as a three-lane highway. Nemeth measured the effectiveness of the TWLTL in terms of average running speed and average running time over the modified section, and in number of brakings and weavings on the highways. He felt that TWLTLs were a success in terms of increasing overall speed and reducing brakings and weavings (which he felt were an indication of too many conflicts).

Nemeth, Zoltan A., "Impact of Two-Way Left Turn Lanes on Fuel Consumption," Transportation Research Record 901, Transportation Research Board, Washington, 1983, p. 32.

This report analyzes the benefits derived from TWLTLs and expresses those benefits in terms of annual reduction in fuel consumption, dependant on driveway density, ADT, and left turn volume. The reduction is compared to the "do-nothing" alternative, and shows significant consumption reductions with two-lane sections, and small, sometimes significant consumption reductions with four-lane sections.

Nemeth, Zoltan A., Two-Way Left-Turn Lanes: A State-of-the-Art Overview and an Implementation Guide, Ohio State University, 1978 pp 13-17, also in Transportation Research Record 681, Transportation Research Board, Washington, 1978, pp. 62-69.

This material analyzed the effectiveness of TWLTLs on the basis of average running speeds and number of "erratic maneuvers" (weavings and brakings) when compared to the "before" condition, which was always no form of median. In conditions where the TWLTL was added with no loss of existing through lanes, the TWLTL was found to decrease the number of erratic maneuvers and usually increased the overall running speeds.

Newman, Earl E., letter to James A. Thompson of February 27, 1979, city of Springfield, Missouri traffic engineer.

According to Mr. Newman's letter, a five-lane section (four through lanes plus a TWLTL) is a traffic engineering tool to be used on existing facilities in order to maximize capacity. He does not recommend it for an initial design of a roadway through relatively undeveloped areas. In that case, he prefers a section involving some sort of median with left turn pockets at intervals. He gives accident and traffic volume data for three different highways in support of his recommendations. Two are five-lane sections with ADTs of 20,000 and 37,000, and the third is a four-lane divided highway with 14,000 ADT. The accident data shows a lower accident rate on the four-lane divided section, with the major difference in accidents showing up in a comparison of mid-block accidents over a 12-month period. The divided section had one-third the accidents of the lower of the two undivided sections over the same time period. Other information gives the capacity of an expressway as 750 vphpl.

Parker, Martin R., Jr., "Guidelines for Selecting Median Treatments for Urgan Highways," Compendium of Technical Papers - Institute of Transportation Engineers 49th Annual Meeting Toronto, Canada, Washington, 1979, p. 77.

This paper was written to present a series of regression equations which were to provide the highway engineer with information concerning the preferred type of median treatment on a certain facility. These equations took into account the ADT, streets and signals per mile, local population and driveways per mile. For each type of median treatment, two equations were developed, one for accident estimate and the other for delay estimates on the facility.

Parker's data was gathered from a sampling of roads in the northern Virginia area with examples of raised, traversable and undivided sections comprising the sample.

Parker, M. R., Jr. and K. H. Tsuchiyama, Traffic Control for Reversible Flow, Two-Way Left-Turn Lanes, State-of-the-Art Report, FHWA-RD-85/010, Federal Highway Administration, Washington, D.C., October, 1984.

The authors present traffic control and effectiveness information for 19 sites with reversible-flow, TWLTL operations.

Parker, Martin R., letter to Mark R. Norman of May 22, 1985, Engineering Consultant, Canton, Michigan.

This letter is addressing seven-lane sections (six through lanes with a TWLTL) and determines that from past data collection, seven- and five-lane sections have similar accident rates. The seven-lane sections mentioned had ADTs in the upper 20,000 range.

Rosenbaum, Merton, "Traffic Control for Reversible Flow Two-Way Left-Turn Lanes", Public Roads, Washington, D.C., June, 1986, pp. 1-10.

The article focuses on driver understanding of signage for this unusual arrangement of lanes. Research results resulted in the proposal of *MUTCD* amendments in 1985 to allow a static sign system as an alternate to lane-use control signals, certain new pavement markings, and a new, non-flashing TWLTL signal.

Royer, David C., letter to Mark R. Norman of May 15, 1985, Principal Transportation Engineer, City of Los Angeles.

Mr. Royer is defending the Los Angeles policy of using TWLTLs whenever possible. The advantages he cite include: reducing travel distance, improved intersection efficiency, reduces left-turn phasing requirements, improves operation of emergency vehicles, reduces maintenance costs, construction traffic routine, eliminates the median as a fixed object, allows for striping revision at minimal cost, and acceptance of the TWLTL by the business community. He also cites the fact that total accident rates have not increased with TWLTL installation.

Savage, William F., "Directional Median Crossovers," Traffic Engineering, August, 1974, Washington, pp. 21-23.

This article explains the concept of indirect left turns at intersections of major roads in Michigan. In an effort to reduce congestion and delay at major intersections, indirect left turns are accomplished by having the motorist turn right onto the major highway and then make a U-turn through a directional crossover to travel in the desired direction. He explains that this concept is used with highways having very wide medians to accomodate the crossover (U-turn) lane, and that it does reduce delay and congestion. Since phasing is reduced at the intersection (no left-turn phasing is necessary), the capacity of the intersection is increased and traffic flows more smoothly.

Sawhill, Roy B., and Jerome W. Hall, "Investigation of Left-Turn Movements on Arterial Streets and Highways", Traffic and Operations Series, Research Report No. 13, Transportation Research Group, University of Washington, November, 1968.

The authors stated that "traffic volumes as such are not always found to be a warrant, but volumes approaching roadway capacities in either direction may be a reason for not installing the TWLTL, more important would be the observations of time gaps of sufficient length for left-turn movements to be accomplished".

Sawhill, Roy B., and Dennis R. Neuzil, "Accidents and Operational Characteristics on Arterial Streets with Two-Way Median Left-Turn Lanes," Highway Research Record 31, Highway Research Board, Washington, 1962, p. 54.

This report, concerning the first TWLTL installation in the country, does address the volumes using a TWLTL. According to their volume counts, the peak hour volume was 232 TWLTL movements/hour. In addition, the overall TWLTL volume was found to be approximately 23% of the total volume counted (over a 12-hour period). The peak hour was the noon hour. The report also shows graphs of the TWLTL volume over the count period. Head-on collisions on TWLTLs were shown to be an uncommon occurrence and of negligible concern.

Shaw, R.B., and H.L. Michael, "Evaluation of Delays and Accidents at Intersections to Warrant Construction of a Median Lane," Highway Research Record 257, Highway Research Board, Washington, 1968, pp. 17-33.

This report presents the results of a study involving the need for left-turn lanes at high-volume intersections. The two determining criteria for the left-turn lane were delay and accident data. The authors determined the cost of the delay and the average cost of an accident, and compared the benefit gained by the installation of a left-turn lane to the cost of the construction and maintenance of that left-turn lane. If the benefit was greater than the cost, it was determined that the lane was worth constructing.

SOAP 84 User's Manual, U.S. Department of Transportation, Washington, 1985, pp. B-19-B-21.

The SOAP 84 user's manual presents a model for the determination of the capacity of an unprotected left turn interval, which could be used for the calculation of the capacity of a TWLTL or other median treatment. The model used for this calculation was taken from the NETSIM model and relates opposing flow and minimum headways necessary for left turn movements.

Stover, Vergil G., et al., "Guidelines for Medial and Marginal Access Control on Major Roadways," National Cooperative Highway Research Program Report 93, Highway Research Board, Washington, 1970, pp. 32-45.

This report advocates left turns from major arterials at intersections only, unless there is adequate median width to provide left turn pockets at specific mid-block locations. TWLTL's are not discussed as an alternative. This report is advocating restricted access as much as possible, allowing any sort of access only if a median of sufficient width is provided for cars to decelerate before a left turn or accelerate after a left turn onto the arterial.

Stover, V.G., et. al., "Chapter 4 -- Access Control and Driveways," in Synthesis of Safety Research Related to Traffic Control and Roadway Elements, Vol. 1, Report No. FHWA-TS-82-232, Federal Highway Administration, December, 1982.

This literature review reports the results of Horne and Walton, Sawhill and Neuzil, Nemeth, and Glennon, et. al. Those results are shown in this annotated bibliography under the respective authors.

Thakkar, Janak S., "A Study of the Effect of Two-Way Left-Turn Lanes on Traffic Accidents, Illinois Department of Transportation, Springfield, 1983.

This report presents the results of a study of highways with TWLTLs and the effect the TWLTLs had on accident rates at high accident locations. In all cases, rates had fallen and the severity of accidents was reduced, also. A benefit-cost analysis was performed and concluded that TWLTLs were an economic and safe alternative on highways with very high levels of roadside development.

Thompson, James A., letter to Tom Brahms of June 26, 1984, transmitting notes of TWLTL Counterpoint meeting held in Chicago.

This meeting stated that TWLTLs were appropriate on minor arterials with low, but mid-block left-turning demands and in situations where no other alternatives were practible. The meeting concluded that TWLTLs were not acceptable for reconstruction of arterial streets, that the need to control conflict points is too great on major arterials.

The meeting also recognized that access to businesses is a problem with raised medians. Consequently, the meeting saw the need to coordinate with businesses the construction of common driveways at access points. At non-developed areas, the conclusion was that the engineer was losing an opportunity to influence future development and access.

Thompson, James A., letter to Mark Norman of May 16, 1985, transmitting TWLTL information gathered during research, city of Des Moines, Iowa.

Mr. Thompson feels that the upper limit for a five-lane section is 25,000 ADT and that 40,000 is too much for a seven-lane section. He uses these limits as the result of research he did for Des Moines which determined the median treatment for an urban arterial, given accident rates, mid-block left turn volumes, and street traffic volumes.

In a report he wrote which was included with his letter he mentions that the accident rate for a four-lane divided arterial is significantly lower than that of a five-lane facility, and that "the midblock accidents on a TWLTL carrying 37,000 vehicles per day are alarming." Also, "If the future land use goals of a community include containment of strip-type commercial development, then the TWLTL is not the best choice."

Transportation Research Board, Highway Capacity Manual - Special Report 209, Washington, 1985, p. 7-3, 11-2.

The new Capacity Manual requires that multilane roads be divided into one of four major types with the following major characteristics: urban or suburban, divided or undivided. The Manual recognizes that there are many different types of median treatments which might categorize a road as somewhere inbetween divided and undivided. It also recognizes that there are several different types of median treatments which involve some sort of continuous left turn lane. The Manual, in general terms, compares the relative capacity of a facility with some sort of median treatment to a similar road without any form of treatment, concluding that a road with a median treatment intended to provide better left turning conditions will have less friction than one without any treatment.

The Manual also states that the determination of a road as rural or suburban depends on several factors, like the frequency of unsignalized intersections, driveways and other uncontrolled access points, and the number of left and right turns into and out of these access points.

The determination of a multilane road as urban or suburban, divided or undivided allows the determination of an "Adjustment Factor for Type of Multilane Highway and Development Environment." The Manual realizes that this method does not recognize various types of median controls explicitly, but advises the user to interpolate between the tabulated values of the Adjustment Factor to compensate for the different types of median treatments.

Chapter 11, Urban and Suburban Arterials, discusses the methodology of determining the level of service of an arterial, but does not discuss the capacity of an arterial, stating that "the capacity of an arterial is generally dominated by the capacity of its signalized intersections. . . . In some cases, there are special midblock restrictions that also limit the capacity." The user is then referred to Chapter 9, Signalized Intersections, for determining the capacity of a signalized intersection.

The new capacity manual, addressing the capacity of unsignalized intersections states that the capacity of an unsignalized intersection is determined by first determining the ideal capacity of the movement, and then factoring that capacity down due to the effects of conflicting movements on the desired movement. Graphs are used to determine both the ideal capacity and the factors for adjustment. These graphs use critical gap length and opposing flow rate and the capacity used by the existing demand to determine the capacity of a movement.

Voorhees, Alan M., and Associates, Quality of Flow in Urban Arterials - Phase I, Federal Highway Administration, Washington, 1978, pp. 19-31.

This report addresses the issue of arterial capacity, and recognizes that the limiting point of arterial capacity may not be at a signalized intersection. Its proposed method of analysis accounts for this.

The general method involves collecting geometric information about a length of arterial as well as volume information and running the NETSIM program using this data. The data collection is complex and tedious, but careful data collection would produce realistic results from the computer simulation. Since the program develops its model based on information gathered in the field, it could be run with data intended to make a section of arterial run at capacity, and could then determine the capacity of the section and therefore determine the capacity of the turning lane or other median treatment.

Walton, C. Michael, et. al., "Accident and Operational Guidelines for Continuous Two-Way Left-Turn Median Lanes," Transportation Research Bulletin 737, Transportation Research Board, Washington, 1979, pp. 43-53.

This paper looked at median treatments based on ADT, level of development, left-turn accidents and total accidents. Tabulated warrants for access control techniques were presented using the parameters just mentioned. It was concluded that TWLTLs produced lower accident rates at intersections, but that one-way left-turn lanes have lower accident rates at mid-block, driveway locations.

Washington State Department of Highways, "Two-Way Left-Turn Lanes", Policy Directive No. 24-15 (HT), Seattle, Washington, September 13, 1973.

The State of Washington uses TWLTLs on multilane roads with ADT between 10,000 and 25,000 and on two-lane roads between 5,000 and 12,500. Their upper limit of 25,000 ADT was echoed by Thompson (1985)

Welsh, Thomas M., "A Report on Median Treatments Utilized for the Improvement of Urban Arterial Streets," Iowa State University, Ames, Iowa, 1980, p. 23.

This paper recommends that arterials with traffic in excess of 15,000 ADT should have a raised median divider with left-turn bays, preferably, with the TWLTL as a second choice. The paper also quotes heavily from Glennon and Harwood's work in terms of choosing appropriate median treatments.

City of Wichita, Kansas, "Economic Factors Affecting Commercial Properties Adjacent to Raised Medians," Traffic Engineering Division, June, 1971, p. 8.

This report measured economic impact on businesses abutting a facility which had recently installed a raised median. Overall results showed an increase in revenue for businesses along the facility and a general increase in property values along the facility after the raised median was installed.

Appendix D

Field Data-Collection Forms

Data Collection Procedure

Several different types of data are to be collected at each collection site. These are: Volume, Travel Time , Roadside Development, Driveway Activities, Length of Study Area, Alignment, Lane Width, Median Width, Left Turning Bay Width and Length, and any valuable information pertaining to a particular site.

Two types of volumes will be collected: Through volumes and left-turning volumes. One person will count the through and the left-turning vehicles in one direction, using a hand tally, and the other counts the other direction in the same fashion. However, left turning vehicles will be counted in two different ways depending on the type of median. At a gap in the median, only vehicles that start at the arterial and make a left turn through that gap will be counted. In a TWLTL location, all left turning vehicles in a length of approximately 1000 feet will be recorded. (See form No.1)

Travel Time will be obtained using Georgia Tech's Van as a floating vehicle. It will be recorded in seconds using a stop watch.

The rest of the data collection will either be a direct measure using a Rolatape (driveway width, lane width, median width, etc.) or a simple observation such as roadside development (see forms 3 and 4).

Field Studies

Three different types of studies will be performed at each individual site. A delay study for Left-Turning vehicles only using the Epson Hx-20 lap top computer running the QUEDEL program.

A vehicle classification study to determine the different types of vehicle that use the study area, such as passenger cars, single unit trucks, etc. Using form No. 5, one person will count the total number of vehicles without regard of type, while another person will count the total number of CD (cars and pick-ups towing light recreational trailers), SU (single unit), 2-S2 (two axle semi-trailer) and 3S-2 (three axle semi-trailer). These counts will be done for 5 minutes in each direction).

Finally, the adequate gap study will be performed using a metronome, set at 60 beats per minute. We will look at only one direction of traffic to determine the duration of clear gaps between successive vehicles. This study will be done at the same time as the delay study.

Field Data Form
for
Median Treatment/TWLTL Project

Form No. 1

Date:__________ Observers:______________________ Weather_____

Location: ____

County:______________ Start Time:_________ End Time: _______

Traffic Conditions (a.m., p.m., off peak): _________________

No. of through lanes (both directions):_____________________

Road direction___________ Type of median treatment ________

Left-Turn and Through Volume Count

a) One person counts the through and the left-turning vehicles in one direction, using a hand tally, and the other counts the other direction in the same fasion. Count for 5 minutes. If you count less than 5 left-turning vehicles total, extend the count to 15 minutes.

Total Volume Count Duration:_________minutes

Direction:_______bound Direction:________bound

Total:___________ Total:____________

Equiv. hourly flow rate______ Equiv. hourly flow rate______

(Multiply by 12 if a 5 minute count, by 4 if a 15 minute count)

Flow rate, sum of both directions:__________________________

Avg. flow rate per lane:________________ Split:______________

b) If counting at a gap in a median, count vehilces that start on the arterial and make left turn through that gap. Also, make note of how many of those vehicles actually make a U-turn instead of just a 90 degree left turn.

If you're at a TWLTL location, pick a length of left turn lane and count every vehicle that uses that length of TWLTL.

Total:__________________ Number of U-turns observed:_______

Equiv. flow rate:_______ % of total rate as left turns:____

Tape QUEDEL results here

Adequate Gap Study

Form No. 2

Location:__________________ From ______________________________
to ______________________________ Date:____________________

This study will be done in the same way that the crosswalk study was done. A metronome, set at 60, will be your timer. Look at only one direction of traffic, and determine the duration of clear gaps, that is, the amount of time between successive vehicles. Time about 100 gaps.

Gap Length (seconds)	Total length	Number of Gaps Av gap____ Std dev_____	Turns made in gap
1		1 ______________________	1 ________
2		2 ______________________	2 ________
3		3 ______________________	3 ________
4		4 ______________________	4 ________
5		5 ______________________	5 ________
6		6 ______________________	6 ________
7		7 ______________________	7 ________
8		8 ______________________	8 ________
9		9 ______________________	9 ________
10		10______________________	10________
11		11______________________	11________
12		12______________________	12________
13		13______________________	13________
14		14______________________	14________
15		15______________________	15________
16		16______________________	16________
17		17______________________	17________
18		18______________________	18________
19		19______________________	19________
20		20______________________	20________

Total: __________

Adequate Gap Study

Form No. 2b

Location:____________________ From ______________________________

to _________________________________ Date:______________________

This study will be done in the same way that the crosswalk study was done. A metronome, set at 60, will be your timer. Look at only one direction of traffic, and determine the duration of clear gaps, that is, the amount of time between successive vehicles. Time about 100 gaps.

Gap Length (seconds)	Total length	Number of Gaps Av gap____ Std dev_____	Turns made in gap
21		21________________________	21_________
22		22________________________	22_________
23		23________________________	23_________
24		24________________________	24_________
25		25________________________	25_________
26		26________________________	26_________
27		27________________________	27_________
28		28________________________	28_________
29		29________________________	29_________
30		30________________________	30_________
31		31________________________	31_________
32		32________________________	32_________
33		33________________________	33_________
34		34________________________	34_________
35		35________________________	35_________
36		36________________________	36_________
37		37________________________	37_________
38		38________________________	38_________
39		39________________________	39_________
40		40________________________	40_________

Total: __________

Field Data Form

Form No. 3

Date:__________ Location:______________________________________

from__________________________ to ______________________________

Direction:_____Bound Travel Time:_______ Distance:_____

No of Driveways:______ Total Length of Driveways:________

Comments:____

____

____

Intersection Spacing:____________ Alignment:______________

No of Lanes:______ Lane Width:__________ Speed Limit:_____

Shoulders:___________________ Median Width:________________

Type of Traffic:____

Roadside Development:____

____

____

____

____

____

____

Driveway Activities:____

____

____

____

____

For Raised Medians:

Left Turn Bay Length:________ Left Turn Bay Width:_______

Type of Control Devices:_______________________________________

Total Driveway Length

Form No. 4

Location ______________________________

Direction: Travelling ______Bound; Driveways _____(N, S, E, W)

of ____________________ (Street) Date: ______________

1. __________ feet to ____________________
2. __________ feet to ____________________
3. __________ feet to ____________________
4. __________ feet to ____________________
5. __________ feet to ____________________
6. __________ feet to ____________________
7. __________ feet to ____________________
8. __________ feet to ____________________
9. __________ feet to ____________________
10. __________ feet to ____________________
11. __________ feet to ____________________
12. __________ feet to ____________________
13. __________ feet to ____________________
14. __________ feet to ____________________
15. __________ feet to ____________________
16. __________ feet to ____________________
17. __________ feet to ____________________
18. __________ feet to ____________________
19. __________ feet to ____________________
20. __________ feet to ____________________

VEHICLE CLASSIFICATION COUNTS

Form No. 5

Date: ____________ Location: ______________________________

from _________________________ to ______________________________

Day: _________________ Observer: ____________________________

In the spaces under ___ Bound enter the types of vehicles you are counting; P, CD, SU, 2-S2, 3-S2.
Note: Cars and pick-ups towing light recreational trailers should be classified as CD, while those towing large heavy trailers are SU.

Begin Time   End Time   _____ Bound

__________   __________   ______ ______ ______ ______

Total ____Bound______

Subtotal= ______ ______ ______ ______

Begin Time   End Time   _____ Bound

__________   __________   ______ ______ ______ ______

Total ___Bound_______

Subtotal= ______ ______ ______ ______

Conclusions: ____

Appendix E

Description of Sites

No.	Location	Type
1T	SR 124 in Lawrenceville	TWLTL
2T	SR 20 in Lawrenceville	TWLTL
3T	Memorial Drive (east of Hairston)	TWLTL
4T	US 78 in Snellville	TWLTL
5T	Candler Road	TWLTL
6T	Cobb Parkway	TWLTL
7T	Old National Highway	TWLTL
8T	Roswell Road (inside the perimeter)	TWLTL
9T	GA-85	TWLTL
10T	Jonesboro Road	TWLTL
11T	Memorial Drive (at Dekalb College)	TWLTL
12T	Roswell Road (outside Perimeter)	TWLTL
13T	Memorial Drive (near I-285)	TWLTL
14T	Buford Highway (north of I-285)	TWLTL
15T	Buford Highway (south of I-285)	TWLTL
16T	Cobb Parkway (near Windy Hill Rd.)	TWLTL
1R	Moreland Avenue	R.M.
2R	Forest Parkway	R.M.
3R	Buford Highway	R.M.
4R	Tara Boulevard	R.M.
5R	GA-85	R.M.
6R	Holcomb Bridge Road	R.M.
7R	Fulton Industrial Boulevard	R.M.

Site Description

For the purpose of this study, a total of 23 sites were selected, 16 Two Way Left Turn Lane (TWLTL) and 7 of the Raised Median type. These sites are further classified in terms of driveways per mile and their Annual Average Daily Traffic (AADT). They are separated as follows:

Low Driveways per mile = Less than 50

Medium Driveways per mile = Between 50 and 100

High Driveways per mile = More than 100

and

Low AADT = Less than 18,000

Medium AADT = Between 18,000 and 30,000

High AADT = More than 30,000

Table 3.1 lists all sites.

S.R. 124 in Lawrenceville:

This site is located inside the city of Lawrenceville extending from Gwinnett Drive to a point 0.2 miles north. It is a TWLTL with an AADT of 17,960 and 75 Driveways per mile. It is mainly lined with a gas station, one restaurant, a Gwinnett County building, one private residence, a decorating store, a furniture store and a large shopping center.

The cross section consists of two 12 feet through lanes (one for each direction) and a 13 feet TWLTL. There is a side-walk on the west side only and no lights are provided on either edge.

The traffic is composed of about 97% passenger cars and 3% trucks and recreational vehicles.

S.R. 20 in Lawrenceville:

This site is located inside the city of Lawrenceville extending from Phillips Street to Applewood Drive, a total of 0.18 miles. The direction of this TWLTL section is East-West and has an AADT of 15,487 and 85 Driveways per mile. To the sides of this roadway you find a shopping center, a Mrs. Winners fast food, 2 private residence, a U-Haul rental store, a Goodyear tire shop and the St. Lawrence Rectory.

The cross section consists of two 12 feet through lanes (one for each direction) and a 13 feet TWLTL. There is a curb on one side of the street, but no sidewalks are provided. Street lights are found on the north side of the section approximately every 300 feet.

The traffic is composed of about 95% passenger cars and 5% trucks and recreational vehicles.

Memorial Drive (east of Hairston):

This is one of the two sites located in State Route 10 near the vicinity of Stone Mountain. It is a TWLTL with an AADT of 28,300 and 35 Driveways per mile. The section extends from Englewood Drive to a point 0.2 miles east. To

the sides of the road you find 2 private residence, an apartment complex, a motel and a sporting goods shop. The cross section consists of six 12 feet through lanes and a 13 feet 6 inches TWLTL. No sidewalks nor lights are provided at this site.
The traffic is composed of about 98% passenger cars and 2% trucks and recreational vehicles.

U.S. 78 in Snellville:

This site is located just outside the city limits of Snellville. It extends from Cindy Lane to a point 0.2 miles east. It is a TWLTL section with an AADT of 22,380 and 60 Driveways per mile. To the sides of the road you find a restaurant, Ken's pizza, a used car place, a private residence, a tax service building and a nursery school. The cross section consists of four 12 feet through lanes and a 12 feet TWLTL. There is a sidewalk on the north side of the section and lights are provided on one side only. The traffic is composed of about 98% passenger cars and 2% trucks and recreational vehicles.

Candler Road:

This site is located near the vicinity of Atlanta. It is a TWLTL and extends from Eastwyck Road to Misty Waters Drive. It has an AADT of 21,530 and 105 Driveways per mile. To the sides of the roadway you will find a liquor store, 4 fast food places, a car wash, a tune up clinic, am empty building and a gas station.

The cross section of this site is composed of four 10 feet through lanes and a 12 feet TWLTL. There are sidewalks on both sides of the road.

The traffic is composed of about 97% passenger cars and 3% trucks and recreational vehicles.

Cobb Parkway:

This site is located in Smyrna which is a suburban area near the vicinity of the city of Marietta. It extends from Spring Road/Circle 75 Parkway to a point 0.2 miles north. It is a TWLTL with an AADT of 45,566 and 65 Driveways per mile. It is mainly lined with 7 fast food places, a Dunkin Donuts, an office building and Service Merchandise.

The cross section consists of four 12 feet through lanes and a 15 feet TWLTL. Both sides have curbs on their sides but no sidewalks are provided.

The traffic is composed of about 97% passenger cars and 3% trucks and recreational vehicles.

Old National Highway:

This site is located in south Fulton County. It extends from Old Bill Cook Road to Jolly Road which adds up to a total of 0.19 miles. It is a TWLTL with an AADT of 45,360 and 80 Driveways per mile. To the sides of this road you find 9 fast food places, some of which share the same driveway, a car wash, an empty lot, 2 banks and wholesale mattress house.

The cross section is composed of four 12 feet through lanes and a 12 feet TWLTL. There is a sidewalk on the west side and no light are provided on either side.

The traffic is composed of about 99% passenger cars and 1% trucks and recreational vehicles.

<u>Roswell Road (inside the perimeter):</u>

This site is located inside the city of Atlanta extending from Rickenbacker Drive to Midvale Drive, or a total of 0.19 miles. It is a TWLTL with an AADT of 32,745 and 65 Driveways per mile. It is mainly lined with a shopping mall, a residence, a fruit stand, a paint shop, an auto sound shop, 2 sets of apartment complex and 2 condominiums.

The cross section consists of four through lanes, 11 feet outside lanes and 10 feet inside lanes, and a 10 feet TWLTL. There are sidewalks on both sides of the road.

The traffic is composed of about 98% passenger cars and 2% trucks and recreational vehicles.

<u>GA-85 (north end):</u>

This is one of the two sites located in S.R. 85 inside the limits of the city of Riverdale. The section extends from Valley Hill Road to a point 0.2 miles south. This TWLTL has an AADT of 36,233 and 140 Driveways per mile. To its sides you find 11 fast food places, a package store, a gas station, an office building, a library, a parking lot and a health food place.

The cross section consists of six 12 feet through lanes, except the outside lanes which are 11 feet wide, and a 12 feet TWLTL. There are sidewalks on both sides of the road as well as street lights approximately every 300 feet.

The traffic is composed of about 97% passenger cars and 3% trucks and recreational vehicles.

<u>Jonesboro Road:</u>

This site is located near Forest Park in Clayton County. It extends from College Street/Thurmond Road to a point 0.2 miles south. This site has an AADT of 32636 and 100 Driveways per mile. It is mainly lined with 3 fast food places, a parking lot, a church, a shopping center, an auto sales place, a body shop and a copy place.

Its cross section consists of four 12 feet through lanes and a 13 feet TWLTL. Both sides have a curb but no sidewalks are provided.

The traffic is composed of about 97% passenger cars and 3% trucks and recreational vehicles.

<u>Memorial Drive (at Dekalb College):</u>

This site is located about one mile outside the perimeter in S.R. 10 extending from the Dekalb College entrance to a point 0.27 miles east. It is a TWLTL with an AADT of 43,395 and 107 Driveways per mile. To the sides of this road you find 7 fast food places, a U-Haul rental place, an auto shop, a CMC stereo store, a rent a car place, an empty building, a plaza and a Color Tile/Pro Golf store.

The cross section consists of six 12 feet through lanes and a 12 feet TWLTL. Both sides have a curb but no sidewalks are provided.

The traffic is composed of about 97% passenger cars and 3% trucks and recreational vehicles.

<u>Roswell Road (outside the perimeter):</u>

This is one of the pilot sections located in the Atlanta suburb of Sandy Springs, extending from Sandy Springs Place to Hilderbrand Drive, or 0.18 miles. It is a TWLTL with an AADT of 35,730 and 115 Driveways per mile. This stretch of road has six restaurants, two office buildings, a used car lot, a boat sales lot, a muffler shop, a pair of real estate offices, two small strip shopping centers and one medium-size shopping center.

The cross section of this site is composed of four 10.5 feet through lanes and a 10 feet TWLTL. Sidewalks are provided on both sides of the road.

Traffic on Roswell Road is predominantly passenger cars and light trucks, with approximately 10% of the total traffic made up of single unit (SU) trucks and buses. Very few tractor-trailer (WB) trucks were observed.

Memorial Drive (near I-285):

This site extends from 0.2 miles east of I-285 to a point 0.2 miles east. It is a TWLTL with an AADT of 55,400 and 55 driveways per mile. To the sides of the road you find two gas stations, a Denny's, Steak'n Shake, Church's Fried Chicken, Wendy's, and a Pizza place.

The cross section consists of six 12 feet through lanes and a 12.5 feet TWLTL. Both sides have a curb but no sidewalks are provided.

The traffic is composed of about 98% passenger cars and 2% trucks and recreational vehicles.

Buford Highway (north of I-285):

This site extends from 0.1 miles north of Longmire Rd. to a point 0.2 miles north. It is a TWLTL with an AADT of 51,400 and 60 driveways per mile. To the sides of the road you find a small commercial center, a Service Merchandise, a business center, Radio Shack, Pizza Inn, Steak'n Shake, and a Pizza-Inn.

The cross section consists of six 11 feet through lanes and a 12 feet TWLTL. Both sides have a curb but no sidewalks are provided.

The traffic is composed of about 98% passenger cars and 2% trucks and recreational vehicles.

Buford Highway (south of I-285):

This TWLTL site extends from McClave Drive to a point 0.2 miles north. It has an AADT of 38,700 and 90 driveways per mile. To the sides of the road you find a gas station, a motel, a Copper Dollar Saloon, an auto shop, Delta Electronics, a computer store, a small commercial center, Pic-A-Deli Pub, and a contact lens center.

The cross section of this site consists of six 11 feet through lanes and a 14 feet TWLTL. Both sides of the road have a curb but no sidewalks are provided.

The traffic is composed of about 99% passenger cars and 1% trucks and recreational vehicles.

Cobb Parkway (near Windy Hill Road):

This TWLTL site extends from 0.2 miles south of Windy Hill Road to a point 0.2 miles south. It has an AADT of 40,500 and 60 driveways per mile. To the sides of the road you find eight car dealers, three on the west side of the road and five on the east side.

The cross section of this site consists of four 11 feet through lanes and a 14 feet TWLTL. Both sides of the road have a curb but no sidewalks are provided.

The traffic is composed of about 98% passenger cars and 2% trucks and recreational vehicles.

Moreland Avenue:

This site extends from the South River Bridge to a point 0.2 miles south. It is a Raised Median with an AADT of 26,904 and 20 Driveways per mile. It is lined with a truck company on both sides. In this 0.2 mile section there are only four driveways, three on the east side of the road and one on the west side.

The cross section of this roadway is composed of six 12 feet through lanes and a raised median with two left turn bay, one for each direction. Both left turn lanes are 12 feet in width and their lengths are 200 and 400 feet for the north and south sides respectively. No sidewalks are provided.

The traffic is composed of about 85% passenger cars and 15% trucks (two and three axles).

Forest Parkway:

This site is located near the vicinity of Forest Park in Clayton County extending from Old Dixie Highway to Hale Road, or 0.41 miles. It is a Raised Median with an AADT of 25,096 and 62 Driveways per mile. To the sides of this road you find a fast food restaurant, a service station, a car clean up place, 4 car dealers, a used car dealer, an auto body shop, a NAPA auto parts store, a cemetery, a battery service station and a Baptist Church.

The cross section of the site consists of four 12 feet through lanes and a raised median with two left turn bays, one for each direction. Both left turn lanes have a width of 10 feet and a length of approximately 75 feet.

Sidewalks are on both sides of the road as well as street lights, which are approximately every 300 feet.

The traffic is composed of about 95% passenger cars and 5% trucks and recreational vehicles.

Buford Highway:

This site extends from the I-285 off ramp to a point 0.2 miles north. It is a Raised Median with an AADT of 51,409 and 35 Driveways per mile. It is mainly lined with two gas station (one on each side), a fast food restaurant and a small shopping center.

The cross section consists of six 12 feet through lanes and a raised median with two one lane left turn bay. Both left turn lanes have a width of 12 feet and their lengths are 320 feet for the north-bound traffic and 170 feet for the south-bound direction. A sidewalk is provided on the west side of the road.

The traffic is composed of about 95% passenger cars and 5% trucks and recreational vehicles.

Tara Boulevard:

This site is located near the vicinity of Morrow in Clayton County extending from Morrow Industrial Boulevard to a point 0.5 miles south. It is a Raised Median with an AADT of 50,703 and 46 Driveways per mile. To the sides of this road you find three fast food restaurants, two gas stations, a parking lot, a radio store, an auto dealer, a motel and three apartment complex.

The cross section is composed of four 12 feet through lanes and a raised median with two one lane left turn bay. Both left turn lanes are 12 feet in width and have a storage length of about 300 feet. No sidewalks are provided at this site.

The traffic is composed of about 96% passenger cars and 4% trucks and recreational vehicles.

GA-85 (south side):

This site is located inside the limits of the city of Riverdale in Clayton County extending from Roundtree Road to GA-138, or 0.37 miles. It is a Raised Median with an AADT of 36,233 and 91 Driveways per mile. It is mainly lined with a fast food restaurant, a gas station, a furniture store, a residence, an auto parts shop, a sport cycle store, an open lot, an empty building, a Baptist Church, a Beauty College, an office building and a Lube-o-Matic workshop.

The cross section consists of four 12 feet through lanes and a raised median with two one lane left turn bay. Both left turn lanes have a width of 12 feet and their storage length is approximately 120 feet. There are no sidewalks provided at this section.

The traffic is composed of about 96% passenger cars and 4% trucks and recreational vehicles.

<u>Holcomb Bridge Road:</u>

This is one of the pilot sections located in the Atlanta suburb approximately 5 miles north of Sandy Springs. It is a Raised Median with an AADT of 47,970 and 70 Driveways per mile. This section of road is lined with two large shopping centers, 2 restaurants, one bank and 2 gas stations.

The cross section consists of six 12 feet through lanes and a raised median with two one lane left turn bay. Both left turn lanes have a width of 12 feet. No paved sidewalks are present, although a level grassed sidewalk at least 10 feet wide is on both sides of the road.

<u>Fulton Industrial Boulevard:</u>

This site is located to the west side of Atlanta approximately 2 miles west of the perimeter. It extends from Wendell Drive to Martin Luther King Jr. Drive, or 0.3 miles. It is a Raised Median with an AADT of 35,883 and 105 Driveways per mile. To the sides of this road you find 6 fast-food restaurants, a Days Inn motel and a car service station.

The cross section consists of six 12 feet through lanes and a raised median with NO left turn bays. A sidewalk is provided on one side of the road.

The traffic is composed of about 93% passenger cars and 7% trucks and recreational vehicles.

E-20-603

DRAFT

Contract Research

GDOT Research Project No. 8602

Interim Report

CRITERIA FOR TWO-WAY LEFT-TURN LANES VS. OTHER MEDIANS

Volume I:
Delay Comparison of Raised Median and Two-Way Left-Turn Median Treatments

by

Peter S. Parsonson, Professor
Joaquin E. Vargas, Graduate Research Assistant

School of Civil Engineering
Georgia Institute of Technology

Contract with

Department of Transportation
State of Georgia

In cooperation with

U. S. Department of Transportation
Federal Highway Administration

April, 1988

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF CIVIL ENGINEERING
ATLANTA, GEORGIA 30332

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SCHOOL OF
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April 6, 1988

Mr. Peter Malphurs
State Materials & Research Engineer
Office of Materials and Research
Georgia DOT, 15 Kennedy Drive
Forest Park, GA 30050

Attention: Ms. Sondra Selph, Research & Development Bureau

Dear Mr. Malphurs:

Criteria for Two-Way Left-Turn Lanes Vs. Other Medians
GDOT Research Project No. 8602
Georgia Tech Research Project No. E-20-G03

The purpose of this project is to develop a set of design criteria for the choice between two-way left-turn lanes (TWLTL) and raised-curb medians, considering both capacity and safety.

Transmitted herewith are 10 copies of Volume I of the Final Report. It is titled "Delay Comparison of Raised Medians and Two-Way Left-Turn Median Treatments." Volume II is the last in the series and is transmitted under separate letter on this same date. It is titled "Accident Comparison of Raised Median and Two-Way Left-Turn Lane Median Treatments."

Volume I introduces the problem, provides a review of the literature, and reports the results of extensive research on delay and capacity by our graduate students John Hibbard, Joaquin Vargas and Steve Celniker. This material is virtually identical to that provided in our Interim Report submitted last October. While our results were complex and difficult to summarize briefly, we do feel that a key conclusion is that raised medians need to be accompanied by service roads to connect the parking lots of contiguous businesses.

The work by Vargas is reported completely herein. The research by Hibbard and Celniker, however, is only summarized. Their complete Masters Special Research Problem Reports were transmitted to the Department by letter of October 16, 1986. We believe that Celniker's report, titled "The Effect of Median Type on Delay at Signalized Intersections," is particularly worthy of your close examination.

Volume I makes mention of accident research performed by our graduate students Marwan Abboud and Chris Squires. The Abboud work was performed on only 19 TWLTL sections and seven raised-median sections; it was fully covered in our Interim Report. It was followed by much more comprehensive work by Squires, who examined 50 TWLTL sections and 32 raised-median sections, statewide. His findings and conclusions are the subject of the Volume II report which, in our opinion, should supersede and replace the earlier work by Abboud.

We hope that you will find this project to have been a good value for your research dollar. We would like to be among those considered in the future for any research project involving geometric design or traffic operations.

Yours very truly,

Peter S. Parsonson
Professor and Project Director

ACKNOWLEDGMENTS

The authors are indebted to Tech graduates John L. Hibbard and Stephen P. Celniker, whose research results are referenced herein. Graduate student Larry Henson was most helpful in providing continuity over the course of the project.

GDOT engineers Doug Weems and Dick Graves promptly provided inventory and accident data, respectively. The authors particularly appreciate the guidance provided by then State Road & Airport Design Engineer, Floyd Hardy, at the very start of the project.

The authors are especially grateful for the comments from GDOT engineer Jim Fincher, who reviewed an earlier submittal prepared by Tech graduate student Joaquin Vargas.

ABSTRACT

Sixteen arterial sections with two-way-left-turn-lane (TWLTL) medians, and seven with raised medians were identified in the Atlanta area as representing a wide range of ADT volumes and driveway densities. Left-turning traffic was observed during peak-volume periods and data recorded on left-turn stops, delay and amount of adequate-gap time for crossing opposing traffic. The data was analyzed to determine the capacity of a TWLTL design, and (along with accident data) to develop a set of design criteria for the design choice between the two types of medians.

The highest delay observed was at two raised-median sites, not the TWLTL sites. It was found that the delay at both types of sites increased exponentially with ADT and was correlated with the product of hourly left-turning and opposing volumes. Regression analyses indicated that the TWLTL design results in less total delay when this product is less than 200,000 and there are fewer than 50 driveways per mile.

A computer simulation study was performed on one TWLTL section to determine the effect of changing it to a raised median. It was found that the delay at the signalized intersections was not much affected, provided U-turns were prohibited there and the median had a mid-block opening. However, delay to left-turners increased sharply. It was

concluded that raised medians need to be accompanied by service roads to connect the parking lots of contiguous businesses.

KEY WORDS: TWLTL, two-way left-turn lane, traversable median, flush median, raised median, curbed median, arterial median, mid-block capacity, mid-block delay, arterial safety

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INTRODUCTION

The report begins with an orientation to the problem that prompted this project. The specific research objectives that were developed are then explained, followed by the benefits that are expected from the project. The potential for implementation of the project results by the Department are stated, and the approved plan of work set forth.

Orientation to Problem

First it is necessary to describe the current state of the art of median-type selection, focusing on the knowledge gaps that indicate the need for further research.

Two-way left-turn lanes (TWLTLs) have been used increasingly as the median of choice. By extending the principle of providing separate storage lanes for left-turn vehicles at intersections, TWLTLs are intended to shadow (provide refuge for) left-turning vehicles from through traffic. Many traffic engineers and highway designers have noticed that the business sector, politicians and the motoring public prefer the TWLTL operation to raised-median designs that restrict midblock left turns. The advantages of the TWLTL have been documented by Nemeth (1), Parker (2), Glennon (3) and others, as summarized herein in the review of literature (Appendix B) and the annotated bibliography (Appendix C). For the purposes of this introduction it is useful to summarize the recent, unpublished experience of the City of Los Angeles (4).

Los Angeles has hundreds of miles of major arterials with high driveway density and continuous strip commercial development. Their typical modern arterial has six through lanes, driveway access to all adjoining properties, a continuous painted TWLTL, and an ADT of approximately 40,000. The City uses the TWLTL as opposed to raised medians for the following reasons, according to one of the L.A. engineers:

- Reduction in circuitous travel distance
- Improved efficiency of intersections through reduction in intersection turning movements.
- Improved operation of the traffic-signal system through elimination of <u>most</u> left-turn phasing.
- Great increase in the operating efficiency of emergency vehicles.
- Reduction in the cost of highway construction and maintenance.
- Accommodation of traffic during construction, maintenance and emergency conditions.
- Elimination of the median-island fixed object, which can be a hazardous obstruction (particularly when operating speed exceeds 45 mph).
- Striping and geometrics can be revised at minimal cost and effort.
- No increase in total accidents, as compared to raised-median operation, according to City statis-

tics gathered over the past 20 years.

If the City of Los Angeles is reasonably satisfied with TWLTL operation on its busy arterials, can there possibly be traffic conditions that demand more of a TWLTL than it can deliver? Is there a point at which traffic volumes, especially left turns, exceed the capacity of a TWLTL? At what loading does a TWLTL break down in operation, no longer providing the capacity and/or safety that could perhaps be obtained from an alternative median treatment?

The literature only hints at answers to these questions. In 1977 the Federal Highway Administration (5) pointed out in its Design of Urban Streets course notebook that he number of movements made in a TWLTL can become too large, with a resultant increase in accidents or near accidents." In the same year Nemeth reported that a questionnaire survey showed that some respondents said that "too many left turns" were a factor contributing to the ineffectiveness of the less-successful TWLTL projects.

When left-turn volumes are very high, a left-turning vehicle may not be able to enter the TWLTL as soon as desired. It may decelerate or even stop in the inside through lane, creating delay to through traffic and a loss of capacity and efficiency. Further, heavy volumes on multiple through lanes may prevent a left-turning vehicle from finding a safe, acceptable gap for an extended period of time. Left-turning vehicles may accumulate in the TWLTL to the point that through vehicles in the inside lane are stopped and delayed. A deterioration is safety, as well as capacity, is apparent under these conditions.

There is a notable absence of capacity data on TWLTLs in the literature. Parker (2) pointed out in 1979 that "In great need of attention is the problem of determining the capacity of alternative median treatments by means of factors other than mid-block delay." The standard references on arterial capacity say little on the subject, because capacity is considered to be limited by G/C ratios at signalized intersections.

In the absence of published research on these points, there are at present no warrants setting forth the upper limits of volumes, especially left-turn movements, for which the TWLTL is an appropriate median treatment. The TWLTL may be overapplied currently, that is, used in locations where it is not as good as an alternative median treatment.

Even in the absence of published material, the problem can be seen and appreciated on Georgia roads and streets. For example, Roswell Road in Sandy Springs frequently has severe congestion of mid-block left-turning volumes, requiring off-duty police to stop traffic to allow these movements. Memorial Drive in Decatur and Stone Mountain is a seven-lane TWLTL design where the danger to pedestrians and turning vehicles is obvious even to the layperson.

State Route 5 in Cobb County was allowed to develop independently on either side of the road. Crossroads are staggered, creating overlap of the left-turn movements. It is difficult to install left-turn signal phasing, and in general the left-turning vehicles find it difficult to compete with one another. Uncontrolled development adds to the dilemma of median selection.

The GDOT State Traffic and Safety Engineer, Mr. Archie C. Burnham, made a presentation on median selection to the Cobb County Board of Commissioners on April 28, 1987 (6). He showed in the table reproduced below the existing and projected accident statistics (per 100 million vehicle-miles of travel) for four facilities in the Atlanta area.

URBAN ARTERIAL ROADS

						85TH	EXISTING RATES			PROJECTED RATES		
	LENGTH	TRAFFIC EXISTING	TRAFFIC FUTURE	DRIVEWAYS PER MILE	STREETS PER MILE	PERCENTILE SPEED	ACC	INJ	FAT	ACC	INJ	FAT
ATLANTA ROAD	5.60	16,000	34,000	31	5.0	46	652	240	2.03	500 (4LD)	200	1.50
										900 (5L)	300	3.00
SOUTH COBB DRIVE	4.12	31,000	40,000	16	4.1	51	725	294	3.22	1100 (5L)	350	3.40
TARA BOULEVARD	9.55	26,300	36,000	26	4.5	52	434	204	1.17	540 (4LD)	220	1.50
HOLCOMB BRIDGE ROAD	1.36	51,600	65,000	31	5.1	49	630	192	1.56	860 (6LD)	250	2.00

Atlanta Roadway is a two-lane in south Cobb County currently being considered by the Department for upgrading to a four-lane divided facility. South Cobb Drive currently has five lanes, including a TWLTL. Tara Boulevard is a four-lane divided highway (meaning that it has a raised median) in Clayton County. Holcomb Bridge Road, in Fulton County, is a six-lane divided route. The table shows that Department projections for Atlanta Roadway indicate that the rate of accidents with a four-lane divided facility will be 500, compared to 900 for an upgrade to a five-lane design (with TWLTL).

Mr. Burnham went on to review the Virginia research by Martin Parker (2), and concluded that the GDOT agrees with his findings and leans toward preferring a raised median section when a) volumes exceed 20,000 per day, b) there are more than 25 driveways per mile, and c) it is feasible to provide sufficient capacity for U turns at the intersections.

He also explained that the Department has performed studies showing that divided facilities hold a substantial edge over TWLTLs in safety performance. They have found accident experience to be related to the number of driveways per mile, the treatment of public streets, pedestrians, sight distance, speed and intersectional capacity. However, the Department has not yet finalized a specific guideline, presumably because further data is needed from additional research such as this present project.

In summary, there has been an unfilled need for research that would provide quantitative (not merely qualitative) guidelines for choice of median treatment. The scope of the research should include not only accident frequency and severity but also volume/capacity considerations. The research should provide a clear answer to the question of what level of traffic volumes, especially turning volumes, is the maximum for both safe and efficient operation of TWLTLs.

Research Objectives

The GDOT has set forth the project objectives as follows:

(1) That a set of design criteria be developed for the use of two-way left-turn lanes (TWLTLs) and raised-curb medians; and

(2) To include a capacity analysis of TWLTLs.

The scope of the research should include not only accident frequency and severity but also volume/capacity considerations. The research should provide a clear answer to the question of what level of traffic volumes, especially turning volumes, is the maximum for both safe and efficient operation of TWLTLs.

Expected Benefits from the Project

The significance of the project is its potential to produce quantitative guidelines--numerical criteria--to assist the designer in choosing, in a systematic way, the proper median treatment for a project. The benefits to be expected from this research are a rational, logical and defensible selection of median treatment that will provide a proper balance between roadway capacity and access to abutting property.

Potential Implementation by the Department

The GDOT is actively engaged in widening two- and three-lane highways to cross-sections that need to be divided using some type of median for purposes of capacity and safety. An example is SR 5 in Cobb County, which is soon to be widened from three lanes to a five-lane section with a TWLTL. The Department is in need of firm data that would help to convince local interests of the proper choice of median type.

Another example is Memorial Drive from I-285 eastward to Stone Mountain. This is a seven-lane section with a TWLTL. There have been 13 fatalities on that four-mile stretch since 1978, and 45 percent of the 800 accidents in 1986 happened in midblock. Therefore the GDOT is proposing to replace the TWLTL with a concrete barrier or a raised median 10-feet wide, with seven U-turn crossings.

If the results of the proposed research had been available in time for these decisions, they would have been used to provide a systematic basis for the median selection.

Work Plan

The approved work plan for the project is included herein as Appendix A. The project began in July, 1986 and finished in March, 1988. The next section of this report provides an overview of the various procedures that were carried out in implementing the work plan.

PROCEDURE

This section of the report explains the steps that were carried out in fulfillment of the approved work plan, which is detailed herein as Appendix A. First there is given a chronology of project phases and personnel, to assist the reader in understanding the various documents that have been produced by the project. The next headings are taken directly from the list of tasks set forth by the work plan.

Chronology of Project Phases and Personnel

It is helpful to begin with a narrative of the way in which the project has been pursued since its beginning in July, 1986.

o During that summer a review of literature and an annotated bibliography were produced; they were submitted to the GDOT by letter of October 26, 1986.

o In that same summer graduate research assistant John L. Hibbard collected extensive data at a TWLTL location on Roswell Road in Sandy Springs, and at a raised-median location on Holcomb Bridge Road one and one-half miles west of Georgia Highway 400. These became the pilot locations for the project Phase I, Design of Methods of Evaluation. Hibbard developed a method for selecting sites, and detailed procedures for data collection. He also developed and tested computerized methods to analyze the gathered data. His findings are summarized later herein.

Hibbard's report (7) was transmitted to the Georgia DOT by letter of October 16, 1986. Hibbard's data-collection procedures are included herein as Appendix D.

o During the summer of 1986 another graduate student, Stephen P. Celniker, studied the effect of median type on delay at signalized intersections. He recorded field data on Roswell Road in Sandy Springs, which is a TWLTL location, and estimated the delay at Hilderbrand Road and Sandy Springs Place if the design had been a raised median instead. Like Hibbard's study, Celniker's work resulted in a detailed Masters report (8) that was transmitted to the GDOT by letter of October 16, 1986. Celniker's findings are summarized later in this report.

o Later that summer graduate students Lawrence Henson and John Hibbard obtained extensive inventory data from Mr. Doug Weems of the Planning Data Services Bureau located in Chamblee. They made use of the Coding and Procedures Manual to begin to determine 10 TWLTL and six raised-median candidate sites based on two criteria: ADT and level of roadside development (measured in driveways/mile).

o In September of 1986 a new graduate research assistant, Joaquin Vargas, began work on the project. With Henson providing continuity from the work of the summer, the two of them drove to many candidate sites. A few were obvious choices, so Vargas hired observers and began field-data collection in October. The GDOT sent review comments on the site list in November, and by early January we proposed a "final" group of 12 TWLTL sites and seven raised-median sites, an increase of three over the 16 we had proposed in the original Work Plan.

o In January, 1987 another new graduate student, Marwan Abboud, began work. He performed accident research for the project, using statistics provided by Mr. Dick Graves of the Traffic & Safety Division, for the 12 TWLTL sites and the seven raised-median sites. His results were transmitted in the Interim Report dated October, 1987.

o Statistical analysis of both the field-collected delay data and the accident data was performed during the winter and spring months. A large number of preliminary plots were generated by the Lotus 1-2-3 computer program. It appeared from these graphs that more sites were needed in order to increase the statistical reliability of the inferences drawn from the data. Vargas and his field crew went to four more TWLTL sites in April and May. He included these sites, for a total of 23, in his delay analysis.

o Like Hibbard and Celniker, Vargas prepared a Masters report to be sent to the GDOT as a supplemental product. It was transmitted to the Department by letter of June 7, 1987. This report went well beyond the Work Plan by applying the microscopic computer simulation program NETSIM to investigate the capacity of a TWLTL. Vargas simulated a section of Memorial Drive in Stone Mountain using this program. He increased the through volumes on this 7-lane arterial, holding the percent of left-turn traffic constant at its observed existing level, to attempt to determine at what volume there would be a breakdown in operation.

o In the summer of 1987 it was decided that Abboud's accident analysis would not be adequate unless the study sites were made longer. Also, we needed many more sites (especially of the raised-median type) so that we could analyze four-lane sections separate from six-lane sections. Therefore another graduate student, Chris Squires, identified 50 TWLTL sections and 32 raised-median sections, statewide, and completed an accident analysis of them in March, 1988. His results were transmitted in Volume II of the Final Report, in April, 1988.

Review of Literature

A thorough review of the literature is included herein as Appendix B. That material groups the literature as follows: 1) Accident research, 2) Operational characteristics, 3) Volume/capacity research, 4) Computer simulation, 5) Comparison of TWLTLs with other median treatments, and 6) Other relevant literature.

Accident-research projects have usually focused on one of two basic methodologies: comparison of accident rates before and after the installation of a TWLTL, or determination of TWLTL effectiveness based on benefit-cost ratios.

Glennon (3) determined in the mid-1970's that the TWLTL is slightly inferior to the raised median where frequent driveways (more than 60 per mile) are in combination with "high" arterial street volumes (more than 15,000). His estimates found it to be a more-effective accident-reduction technique when the roadside is developed to less than 30 driveways per mile and ADT is less than 5,000.

Parker(2) in Virginia developed a set of regression equations requiring four input variables: ADT, numbers of cross-streets and signal per mile, local population, and driveways per mile. His conclusion was that a TWLTL is safer when the number of streets per mile is low (say, 5), regardless of the number of signals per mile, ADT and city population. However, when the number of streets per mile increases to 15, a raised median is preferred, regardless of the number of signals or driveways, or traffic volumes. Because raised curbs are fixed objects, Parker stated that raised medians should not be used when operating speeds exceed 45 mph.

The most-recent accident research was reported by Harwood in 1986 (10). Unfortunately, the groupings for ADT extended only up to 20,000, with one category for ADTs over 20,000 to cover high-volume arterials. A pervasive problem in accident research has been inadequate consideration of major arterials with ADTs of 30,000 to 70,000.

Benefit-cost-ratio research by Harwood and Glennon (11), and also by Thakkar (12), has uniformly shown that a TWLTL is preferred, even for high levels of ADT and roadside development. This is because of the low initial construction cost.

Regarding operational characteristics, Nemeth (1) found that in two out of three cases the installation of TWLTLs increased running speeds.

The concept of a "capacity" of a mid-block section with a TWLTL is not covered well in the literature. The current edition of the Highway Capacity Manual (13) provides no assistance. Fisher (4) observed TWLTL operation to be "satisfactory at best" on seven-lane facilities with ADT of 40,000 in Los Angeles. Lebel (14) stated that a five-lane section near Grand Rapids, Michigan is not operating as well at 40,000 ADT as it did at lower volumes. The State of Washington (15) has an upper limit of 25,000 ADT for their TWLTL designs. Thompson (16) echoed that upper limit for a five-lane design, and stated that 40,000 exceeds the practical capacity of a seven-lane road.

The Georgia Division of the Southern Section, ITE, performed a literature search cited by Nemeth (1). The Georgia group recommended that the TWLTL design be used on five-lane roads with ADTs in the range of 10,000 to 25,000. They concluded that the benefits of a TWLTL become questionable as volumes approach capacity, due to the lack of gaps (in opposing traffic) needed to make left turns.

Sawhill and Hall (17), also, stated that a basis for deciding whether to install a TWLTL would be the observation of time gaps of sufficient length for left-turn movements to be accomplished.

Although there are several computer-simulation models (18, 19, 20) that could potentially be used to help determine the capacity of a TWLTL, none has produced results of any significance. McCoy (20) designed his program TWLTL-SIM to abort left turns when those turning movements cause jammed flow. When such a jam is encountered we could speculate that probably most motorists will decide to drive on to the next free-flow location and make a U-turn. There seems to be no provision in McCoy's model for this.

Some of the literature focuses on comparisons of TWLTLs with raised or depressed medians. Most of this material is in the form of design guidelines. The current AASHTO "Green Book" (21) states that any form of access control should limit the number of conflict points, separate basic conflict areas, reduce maximum deceleration requirements, and remove turning vehicles from through lanes. The Federal Highway Administration (5) recommends TWLTLs for their capacity to store left-turning vehicles safely. They mention that very high concentrations of vehicles at raised-median openings could contribute to degradation of flow.

<u>Development of Method to Examine Roads</u>

We met with Mr. Doug Weems of the Planning Data Services

Bureau, GDOT, located in the Chamblee office. He provided inventory data for our use in determining the locations of roads with median treatments including TWLTL (actually coded as an auxiliary lane, not a median) and raised-curb medians. He provided the 1985 edition of the Systems Inventory Coding and Procedures Manual. In accordance with the Work Plan, we limited our scope to sites close enough to Atlanta to be visited without overnight travel.

Attempts to use photologs to determine road alignment, major intersection spacing, and the level and type of roadside development proved to be less than completely satisfactory, partly because the photologs were several years old. Therefore all candidate sites were visited by project personnel.

<u>Selection of Field Data-Collection Sites</u>

In accordance with the Work Plan, it was attempted to find the following sites: 10 TWLTL sites (total) falling into three ADT categories: less than 18,000, between 18,000 and 30,000, and greater than 30,000. Also 6 raised-median sites falling into two ADT categories: less than 30,000 and greater than 30,000. For each volume category, sites were sought with driveway densities in three ranges: less than 50/mile, between 50 and 100/mile, and greater than 100/mile.

By letter of October 16, 1986 we proposed 10 TWLTL and six raised-median locations as candidate sites for data collection. After receiving comments from the Department on November 4 we made appropriate changes and submitted a final list on January 9, 1987 showing 12 TWLTL and seven raised-median sites. That was the grouping used by Abboud for his analysis of accidents. Vargas, also, did his delay research on these 19 sites, but decided in May of 1987 to add four TWLTL sites in order to enlarge the data base of sites with high ADT (over 30,000) and driveway densities in the range of 50 to 100 per mile. That made a total of 23 sites for his delay work. Of the 23 sites listed next, the four that were added are indicated by an asterisk.

Raised-Median Sites

ADT	Driveways	Location
Less than 30,000	Less than 50/mi	SR 42, Moreland Ave., from South River Bridge (which is 0.2 mi south of South River Indus. Blvd to a point 0.2 mi south, ADT 26,904, drives 20/mi (Site 1R)
	50-100/mi	Forest Parkway from Old Dixie Rd to Hale Rd, ADT 25,096, drives 62/mi (Site 2R)
	More than 100/mi	No sites
More than 30,000	Less than 50/m	Buford Highway from I-285 north 0.2 mi (Krystal/Eye-Rite), ADT 51,409, drives 35/mi (Site 3R)
		Tara Blvd from Morrow Indus Blvd south 0.5 mi (second gap), ADT 50,703, drives 46/mi (Site 4R)
	50-100/mi	Ga 85 from Roundtree Rd to Ga 138, ADT 36,233, drives 91/mi (Site 5R)

		Holcomb Bridge Rd from Graimes Bridge Rd to Old Roswell Rd (Pilot Section), ADT 47,972, drives 70/mi (Site 6R)
	More than 100/mi	SR 70, Fulton Industrial Blvd from Wendell Dr to Martin Luther King, Jr. Dr, ADT 35,883, drives 105/mi, (Site 7R)

TWLTL Sites

ADT	Driveways	Location
Less than 18,000	Less than 50/mi	No sites
	50-100/mi	SR 124 in Lawrenceville, from Gwinnett Dr north 0.2 miles, ADT 13,854, drives 75/mi (Site 1T)
		SR 20 in Lawrenceville, from Phillips R to Appleton Rd, ADT 15,487, 87 drives/mi (Site 2T)
	More than 100/mi	No sites
18,000 to 30,000	Less than 50/mi	Memorial Drive (US 78, SR 10) east of Hairston Rd, from Englewood Dr to a point 0.2 mi east, where a raised median starts, ADT 28,300, drives 35/mi (Site 3T)
	50-100/mi	US 78 in Snellville, from Cindy Lane east 0.2 mi, ADT 22,380, drives 60/mi (Site 4T)
	More than 100/mi	Candler Road from Misty Waters to Eastwyck Rd, ADT 21,538, drives 105/mi (Site 5T)
More than 30,000	Less than 50/mi	No sites
	50-100/mi	Cobb Parkway from Spring Rd/Circle 75 Parkway north 0.2 mi, ADT 45,566, drives 65/mi (Site 6T)
	*	Cobb Parkway from 0.2 mi. south of Windy Hill Rd. to a point 0.2 mi

south, ADT 40,500, drives 60/mi (Site 16T)

Old National Highway from Old Bill Cook Rd to Jolly Rd, ADT 45,366, drives 80/mi (Site 7T)

Roswell Rd from Midvale Dr to Rickenbacker Dr, ADT 32,745, drives 65/mi (Site 8T)

* Buford Highway north of I-285 from 0.1 mi north of Longmire to a point 0.2 mi. north, ADT 51,400, drives 60/mi (Site 14T)

* Buford Highway from McClave Drive to a point 0.2 mi. north, ADT 38,700, drives 90/mi (Site 15T)

* Memorial Drive from 0.2 mi. east of I-285 to a point 0.2 mi. east, ADT 55,400, drives 55/mi (Site 13T)

More than 100/mi

Ga. 85 from Valley Hill south 0.2 mi.(to Del Taco/Taco Bell), ADT 36,233, drives 140/mi (Site 9T)

Jonesboro Rd from College St/Thurmond Rd south 0.2 mi., ADT 32,636, drives 100/mi (Site 10T)

Memorial Dr from entrance to DeKalb Community College northeast 0.27 mi, ADT 43,395, drives 107/mi (Site 11T)

Roswell Rd from Sandy Springs Pl to Hilderbrand Rd (Pilot Section), ADT 35,736, drives 115/mi (Site 12T)

Study sections for TWLTLs were selected to be 1000 feet long. That range did not include any signalized intersections, and unsignalized intersections with minor streets were avoided to the greatest extent possible. (Vehicles turning left into a minor road were not counted).

If the study section had a raised median, left-turning volumes were counted at a median gap which does not provide a direct left turn into a minor cross street.

Field-Data Collection

The details of the field-data-collection procedure were developed and described by Georgia Tech graduate student John Hibbard in his Masters Special Research Problem (7). Appendix D herein summarizes the field procedure and includes the five data-collection forms that were developed for this project.

Hibbard's procedures were developed at the two pilot sites (Roswell Road for the TWLTL site and Holcomb Bridge Road forthe raised-median location). His procedures were adopted by Vargas for the performance of the main project (following the pilot work). However, there were two differences in the field work performed by these two investigators, as follows.

Hibbard went to each of his two sites 15 times each, for about 20 minutes each time, at various times of day designed to ensure that the peak period was not missed. He observed both left turns simultaneously and logged them without differentiation as to direction.

Vargas went to each of his 23 sites two times each, for about 40 minutes each time, at the peak periods determined by studying volume counts and asking the local traffic engineer. One time of day typically was 1 pm and the other was 5 pm. Vargas observed one left-turning movement at 1 pm and the other at 5 pm, always observing the more critical of the two directions. He performed his own studies of Roswell Road and Holcomb Bridge Road, rather than use Hibbard's data, so that each left-turning movement would be correctly represented, separate from the other, in his report.

The field data collected included volume, roadside development, driveway activities, length of study area, travel time over that length, lane width, median width, and left-turning-bay width and length.

Through volumes were counted in both directions. At raised-median sites, left turns through the selected median break were counted. At a TWLTL location all vehicles that turned left over the 1000-foot study area were counted.

Both delay to left-turning vehicles and gaps available for left turns were studied simultaneously for 15 minutes. (There were never any delays observed to through traffic, except on Fulton Industrial Boulevard, where the raised-median design lacks left-turn bays at some median breaks). Left-turn delay was measured using hand-held microcomputers and the QUEDEL program written by the University of Florida to measure the delay to a queue of vehicles. Refer to Hibbard's Appendix B for details (7). At the same time as the QUEDEL study was in progress, another observer measured the gaps in oncoming traffic opposing the left turns. This was done using a metronome set to give an audible click 60 times per minute. The minimum acceptable gap was typically observed to be 5 or 6 seconds, and the study produced the amount of adequate gap time in minutes per hour.

One travel time run was performed in each direction using the floating-vehicle method. In no instance was there observed any delay caused by left-turning traffic, so a single run was considered sufficient and no analysis was performed beyond calculating the speed.

A 5-minute vehicle classification study was performed in each direction, to determine the percentages of cars and various types of trucks using the arterial.

Field-Data Analysis

Hibbard prepared scatter diagrams of the raw field-data in order to arrive at a preliminary indication of the potential for significant relationships between delay and various independent variables. Because there are a number of independent variables, and only one at a time can be shown in a two-dimensional graph, Hibbard went on to perform multiple linear regression analyses using the Biomedical Data Package (BMDP Statistical Software) installed on Georgia Tech's CYBER mainframe computer (22). Hibbard chose this program over others, such as MINITAB, because BMDP has a program known as P9R, the All Possible Subsets program. Hibbard (7) explained this program as follows:

This program begins by estimating one-variable equations with each independent variable alone. The one-variable equation with the highest R^2 is then used as the basis for two-variable models, developed from the one-variable models by adding each other variable separately to the one-variable equation. The best two-variable model is taken, and three-variable models are developed using the two-variable model. This process is continued until there are no more variables to add. The best model is chosen on the basis of the sample R^2, the adjusted R^2 and the Mallows C_p statistic.

Field-data analysis by Vargas, for his 23 sites, was similar to Hibbard's except that Vargas used directional volumes rather than volumes that had been summed for the two directions, as explained above. Also, Vargas used as an independent variable the product of a left-turning volume and the opposing (oncoming) through volume. Traffic engineers commonly calculate this product as an indicator of the need for a protected left-turn phase at a signalized intersection, so Vargas looked at the product's usefulness in estimating median-design-related delay.

FINDINGS

This section presents Hibbard's findings (7) for delay at the two pilot sites; Vargas' results (9) for delay at his 23 sites; Celniker's findings (8) on the effect of median type on delay at signalized intersections.

Hibbard's Findings for Delay at the Pilot Sites

As explained earlier, Hibbard performed a Masters Special Research Problem Report that was transmitted to the GDOT by letter of October 16, 1986. He gathered and analyzed data on delay at the pilot TWLTL site (Roswell Road in Sandy Springs, a five-lane section) and at the pilot raised-median site (Holcomb Bridge Road west of Ga. 400). His procedure was summarized above.

Hibbard's principal findings were as follows:

o At the TWLTL site the delay per left-turning vehicle increased dramatically when the two-way through volume reached 2800 vph. (Hibbard did not convert this through volume into an equivalent ADT, but he could have done so easily; an urban peak-hour volume is about 10 percent of ADT, so the 2800 vph is equivalent to an ADT of about 28,000 vpd).

o At the raised-median site the delay per left-turning vehicle showed no increase as two-way through volumes increased up to the maximum observed value of over 3,700 vph, corresponding to an equivalent ADT of about 37,000 vpd. For reasons undetermined as yet, left-turn delay was found to decrease to only about 10 seconds per vehicle at high values of through volume.

o When compared at equal through volumes, the delay to left-turning vehicles at the raised-median site was consistently less than the delay at the TWLTL site.

o The maximum delay to left-turning vehicles ever observed in the study was greater at the TWLTL site than at the raised-median site. This occurred despite the fact that the raised-median site carried higher through volumes, and had a higher percentage turning left, than did the TWLTL site. The maximum delays were 39 and 30 seconds per vehicle for the TWLTL and raised-median sites, respectively.

Hibbard speculated that delay per left-turning vehicle was higher at the TWLTL site because the driveway density was much higher there (144 driveways/mi) than at the raised-median site (53).

Hibbard attempted with mixed success to use linear regression to develop a useful model that would estimate delay to left-turning vehicles from data on through volume, adequate gap time in minutes per hour, and the percentage of left-turning vehicles that must stop. The model for his TWLTL site had an R^2 of only 53 percent. He was more successful with his raised-median site, with 72 percent; however, it would not be easy for an engineer to predict future values of adequate gap time and stop percentage, so his model is hard to use.

Vargas' Findings for Delay at 23 Sites

It was explained above that Vargas prepared a Masters Special Research Problem Report (9) that was sent to the Department on June 7, 1987. As noted already, he gathered delay-data at 16 TWLTL locations and seven raised-median sites.

The largest total delays observed by Vargas in the entire project were at two raised-median sites: Tara Boulevard near Morrow, and Buford Highway just north of the interchange with I-285. Each has an ADT of about 51,000 and a driveway density of less than 50 per mile.

The largest total delays at the TWLTL sites were noticeably lower than those at the two raised-median sites just mentioned. The most-delayed TWLTL locations were found to be Buford Highway north of I-285 (just north of Longmire Road), Cobb Parkway just north of I-285, Old National Highway, and Memorial Drive at DeKalb College. At 51,000 ADT, the Buford Highway location is as busy as the two raised-median sites, and has more driveways (60 per mile), but less total delay. The other three TWLTL sites have 10 percent less traffic (about 45,000 ADT), and driveway densities ranging from 65 to 107.

Vargas' analyses began with an attempt to correlate delay with just one variable at a time. Regression analyses using only the product of the left-turn volume and the opposing (oncoming) flow were especially successful with the TWLTL sites; his model explained 81 percent of the variation from site to site. The equation is as follows:

$$TD = 0.008643 + 0.000002(LTV \times OppVol)$$

where TD = total delay for TWLTL in veh-hr/hr

LTV = left-turn volume in vph, and

OppVol = opposing volume in vph

Traffic engineers will recognize that the product of these two volumes is commonly used in determining whether a signalized intersection needs a left-turn arrow because of a delay problem. The fact that we are multiplying two volumes together means that delay goes up exponentially as traffic volumes increase on an arterial with a TWLTL. That is, total delay on a TWLTL arterial goes up with the square of the flow. This relationship can be used to help understand Vargas' data for delay for TWLTLs, as follows. First, consider a "base" ADT of 15,000 to be typical of an arterial where a TWLTL is unquestionably a reasonable choice. Vargas found a total delay level of about 0.07 veh-hr/hr at that ADT. Now, if we double the ADT to 30,000, delay should quadruple to 0.28. This is very close to what he found. If instead we triple the base volume from 15,000 to 45,000, the delay should rise as the ratio of 45 squared to 15 squared, which is a factor of 9. Vargas in fact found that the delay increased from 0.07 to about 0.63.

For raised medians, Vargas found that the product of the two volumes was not nearly as well correlated with delay; only 52 percent of the variation from site to site was explained by the model. Delay was found to increase exponentially with increase in ADT, just as was found for TWLTLs. For ADT in the range of 25,000 to 35,000, delay at the raised-median sites was comparable to that observed at the TWLTL sites. However, when ADT reached 50,000, Vargas found much higher delays at two of the raised-median sites than he had encountered at any TWLTL location. Those sites were Buford Highway just north of I-285, and Tara Boulevard.

Using multiple regression analysis for both TWLTL and raised-median sites, Vargas was able to improve on his single-variable findings. For both types of designs he found that total delay was modeled best using the number of driveways per mile, the percent of left-turning vehicles that must stop, and the opposing through traffic volume. His equation for TWLTL explains 87 percent of the variation in delay from site to site, as follows:

$$TD = -0.0498 + 0.00303\ PSt - 0.00131\ Dr + 0.000002378\ M$$

where TD = total delay in veh-hr/hr/1000 ft

PSt = percent left-turn stopped,

Dr = driveways per mile, and

M = product of hourly left-turn and opposing volumes

Vargas' equation for raised medians explains 71 percent of the variation, as follows:

$$TD = 0.0719 + 0.0116728\ PSt - 0.008514\ Dr + 0.00000105\ M$$

Both equations yielded a negative coefficient for the number of driveways per mile. Parker, also, found this correlation negative (9). This goes against our expectancy and probably means that the number of driveways per mile is highly correlated with an unknown variable that has a strong negative influence on total delay.

Vargas solved his regression equations for various traffic and geometric conditions in order to determine which median design produces less delay. One conclusion follows:

o When the product of the hourly left-turn volume in one direction and the opposing volume exceeds 600,000, a raised median produces less delay, regardless of the number of driveways or the left-turn percent stopped. However, this conclusion is actually a theoretical prediction; none of the TWLTL sites had a product anywhere nearly as great as 600,000, and only one raised-median site (Buford Highway) was in that stratospheric volume level. That section of Buford Highway had much more delay than any real-life TWLTL studied, so this conclusion should not be taken as true without more research.

His next two conclusions are based on the assumption that at least 60 percent of left-turning vehicles must stop. (He found this to be true most of the time for both median designs):

o When the product of the hourly left-turn volume in one direction and the opposing volume exceeds 300,000 and there are 80 or more driveways per mile, a raised median results in less total delay. This conclusion, like the previous one, needs to be accepted cautiously. The one TWLTL site (Memorial Drive at DeKalb College) with a product over 300,000 actually had less delay than the one raised-median site with so high a product (Buford Highway). However, the regression equation predicts that Buford Highway would greatly improve in delay if the driveways were increased from the actual 35 to over 80.

o When the product of the hourly left-turn volume in one direction and the opposing volume is less than 200,000 and there are less than 50 driveways per mile, a TWLTL results in less total delay. Our data show that the ADT can be as high as 50,000 without exceeding a product of 200,000, as for example at Tara Boulevard and Holcomb Bridge Road (both raised-median sites with substantial delay). Moreover, the TWLTL section with the highest ADT (Memorial Drive near I-285, ADT 55,400) did not exceed a product of 121,000 during our observations. So, the specification of a product of less than 200,000 in no way limits the category to low-ADT arterials. Inasmuch as this product is useful over a wide range of ADT, and since our observations included sites of both types with driveways on either side of, and close to, 50 per mile, this conclusion ought to be valid for the purposes of the Department.

Celniker's Findings on Delay at Signalized Intersections

As explained earlier, Celniker performed a project leading to a Masters Special Research Problem Report (8) that was transmitted to the GDOT by letter of October 16, 1986. His work was quite different from that performed by Hibbard and Vargas, so his procedure needs to be explained prior to discussing his findings.

Celniker studied only one location, namely the TWLTL site on Roswell Road between Hilderbrand Road and Sandy Springs Place. (That is the same portion of Roswell Road used by Tech's other researchers). First, he assigned each driveway to a "driveway group". All driveways in a group are connected to one another, so that a driver can turn into any one of them to reach any of the businesses served by the common parking lot. Six driveway groups were designated along the west block face, and four along the east face. Then he performed extensive volume counting, during six times of day, of the left turns into and out of each driveway group. Volumes at the intersections with Hilderbrand Road and Sandy Springs Place were also counted during the same six periods.

Celniker then developed computer models for four median-type scenarios, as follows:

o Model 1 - Existing situation, with TWLTL. Observed volumes were entered into the model without change.

o Model 2 - Continuous raised median with no openings but with left-turn lanes cut into the median at the intersections. All mid-block left-turning vehicles that used the TWLTL in Model 1 are modeled to go to an intersection, make a U-turn, and complete the desired movement.

o Model 3 - Raised median with one opening in the middle of the block, with left-turn cut-outs.

o Model 4 - Same as Model 3, except that U-turns are prohibited at the intersections; drivers that in Model 3 were allowed to make these U-turns are instead modeled as through traffic at the intersections and as U-turns at the next median opening.

For Models 2,3 and 4, all of which include raised medians, Celniker widened Roswell Road to include shoulders to ease the U-turns. He also took into account the fact that the pedestrian-minimum-green timing at the signalized intersections could be calculated to be enough only to allow the pedestrian to reach the raised median. He therefore was able to reduce minimum green times in Models 2,3 and 4 to 3 seconds less than that used in Model 1. That adjustment tended to reduce intersection delay in the raised-median models.

Celniker then utilized the Signal Operations Analysis Package (SOAP) to analyze intersection counts and determine the total intersection delay for each model. As compared to the TWLTL model 1, raised-median models 2 and 3 caused large percentage increases in intersection delay, particularly at Sandy Springs Place. Model 4, however, increased delay at Hilderbrand by less than 1 percent. At Sandy Springs Place, intersection delay increased 6 to 12 percent in Model 4, but decreased by 5 percent during 4:00 to 6:00 pm and decreased by 1 percent on weekends and holidays. The reason for the reduction during these two periods is that traffic exiting Sandy Springs Place is so low. The reduced ped-minimum green timing (used with the raised median) is operative under low vehicle-volume conditions, so the shorter cross-street greens reduce intersection delay more than rerouted traffic increases it. Celniker concluded as follows:

> Model 4 clearly maximizes the benefits of a raised median from the standpoint of intersection delay. Delay-inducing exclusive left-turn phases are reduced sharply by banning U-turns, while the increase in through traffic has small effect. The other benefits of raised medians remain--separating opposing traffic, limiting midblock left turns to a single point, and restoring a perception of safety.

Celniker also determined the delay to rerouted vehicles, defined as the delay in driving the rerouted distance, plus the delay at an intersection, plus the delay while waiting for an acceptable gap in oncoming traffic to make a U-turn or left turn. (Of course, Celniker took into account that motorists using a TWLTL must wait for an acceptable gap, also). He found that each of the raised-median models (2,3 and 4) increased delay sharply over the TWLTL model (1). Model 3 had the least of the increases because it has a median opening and allows U-turns at intersections. Even for Model 3, however, delay was two to five times greater (depending on time of day) than for the TWLTL model.

Celniker concluded that, at the study site, a raised median would increase delay, primarily because of the lack of interconnection of the driveways and parking lots. He concluded that the best way to minimize the delay induced by raised medians is to persuade land owners to allow access between neighboring parking lots. He could come to no conclusion on the merits of prohibiting U-turns at signalized intersections; this control reduces total delay at the intersection but greatly increases delay to rerouted vehicles.

COMPARISONS WITH RESULTS OF EARLIER STUDIES

This section discusses the extent to which the findings of the present study are in harmony with, or represent a departure from, those of previous researchers.

The literature is so weak in the area of delay associated with the two types of median designs that it is difficult to make comparisons. Earlier herein a review of literature suggested an upper limit of 25,000 to 40,000 ADT for the TWLTL design. Hibbard's findings at the two pilot sites suggested that the delay per left-turning vehicle at a TWLTL site increases very significantly when the ADT exceeds about 28,000. However, Vargas found that this is true for both kinds of median design; delay goes up exponentially with increase in ADT. Vargas found delay to be about the same for both designs, ADT for ADT. However, he found that when ADT reaches about 50,000 a raised-median design may experience much more delay than a TWLTL.

This finding by Vargas seems to be in harmony with the work of Tech student Celniker, who found that changing a section of Roswell Road from TWLTL to a raised-median design would increase delay.

CONCLUSIONS

Regarding delay, the following conclusions can be drawn from the present research:

o Overall, it was found that the difference in the two designs in delay for turning vehicles was insignificant.

o There is a potential for delay with the TWLTL design that we were unable to quantify in this project. A vehicle exiting a driveway of any type--residential or commercial--and desiring to turn left onto a TWLTL facility, may have to wait for an extended period before the turn can be safely made. Meanwhile, delay is accruing not only to that vehicle, but potentially to a number of vehicles that may be queued behind that car. A raised-median design will force right turns only, eliminating this potential source of delay.

o ADT alone is not a good indicator of the delay to be expected from either median design. Delay increases exponentially with ADT for both designs. However, when ADT becomes high, around 50,000, there is a potential for much greater delay with a raised median than with a TWLTL. This potential is a reality at Tara Boulevard and Buford Highway just north of I-285.

o The TWLTL design results in less total delay to left-turning vehicles than does the raised median design in those locations where the product of the hourly left-turn volume (in one direction over a 1000-foot section) and the hourly opposing (oncoming) volume is less than 200,000 and there are fewer than 50 driveways per mile. There seems to be no ADT equivalent for the 200,000.

o Just as reported in previous research by others such as Parker in Virginia (9), the present research found that delay <u>decreases</u> with increasing driveway density, for both median types. It seems that the number of driveways per mile is highly correlated with an unknown variable that has a strong negative influence on total delay.

o When a raised-median design is selected, delay at signalized intersections can be minimized by prohibiting U-turns there, forcing them to be made at the next median opening. Delay-inducing exclusive left-turn phases are reduced sharply by prohibiting the U-turns, while the increase in through traffic has small effect.

o Even if a mid-block median opening is provided and U-turns are allowed at intersections, a raised-median design will increase delay to left-turners by a factor of two to five over what they would experience with a TWLTL.

o The key to reducing delay to left-turners using a raised-median facility is to provide access between contiguous parking lots. Normally this is done by means of service roads paralleling the arterial and connecting to it at the median openings.

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Appendix A

Approved Work Plan

APPROVED WORK PLAN

PHASE I: Design of Methods of Evaluation

A. Complete a review of literature relating to median treatments.

   1. Complete an annotated bibliography on median treatments.

   2. Prepare a detailed literature review.

B. Develop a method of examining roads including a preliminary list of factors for consideration.

   1. In cooperation with the GDOT Planning and Programming Division, determine locations of roads with TWLTLs and medians and the speed limits and volumes for these roads.

   2. Determine preliminary list of factors to be quantified by data collection.

   3. Use photologs to determine road alignment, major intersection spacing, and the level and type of roadside development (including the number of driveways per mile).

   4. Request GDOT permission to visit sites lacking inventory or photolog data.

   5. Select methods to measure volume, stops, delay and overall travel speed during peak periods.

C. Select field data collection sites, gain approval from the GDOT.

   1. Review inventory of sites to identify potentially excessive volumes. Request GDOT permission to visit sites. Count midblock volumes, record driveway activity, and videotape any operational problems observed.

   2. Select a TWLTL and a site with a median to be used as the

pilot sections for use in testing data-collection procedures.

3. Plan sampling details for measurement of through and left turning volumes, conflicts, stops, delay and overall travel speeds. Determine observation section length and location-specific data needs (signalized intersection and delay data). Also determine sampling methods for determination of delay to vehicles desiring to turn left onto road from driveways.
4. Purchase microprocessor-based hand tallies, repair air-tube-type volume counters, prepare van for field studies, repair computer equipment.
5. Hire and train field observers.
6. With GDOT permission, collect data from Pilot Sections to determine if data collection techniques are adequate.
7. Select statistical techniques for office analysis.
8. Apply statistical techniques to determine the number of field data collection sites needed. Preliminary estimate is 10 TWLTL sites and 6 median-related sites, but this is subject to change based on Tech's experience in locating suitable sites, and on limitations of budget and time. These sites will be chosen based on two criteria: ADT and level of roadside development (measured in driveways-/mile). Optimally, TWLTL sites would fall into three ADT categories (less than 18,000, between 18,000 and 30,000, and greater than 30,000) and median sites into two volume categories (less than 30,000 and greater than 30,000).

For each volume category, sites would be selected with driveway densities in three ranges (less than 50/mile, between 50 and 100/mile and greater than 100/mile).

9. Meet with GDOT; together make final selection of field data collection sites and data to be collected.

PHASE II: Collection of Data and Evaluation

A. Select computer type and statistical software; design coding forms.

C. Collect field data at approved sites and perform office coding concurrently.

D. Develop concept of Median Performance Index (MPI). This will be an linear combination of stops and delay which will indicate the effectiveness of a specific median treatment on a specific road, where a large MPI would indicate a large amount of stops and delay. The MPI would also take into account the delay of the vehicles turning onto the road.

E. Perform a capacity analysis of TWLTLs. Also determine effects on capacity caused by vehicles turning onto the road from driveways.

PHASE III: Report Preparation

This phase will result in a written report which will document all details of the collection of data and its evaluation. Based upon the results presented in the report, further research on this topic may be desired.

Appendix B

Review of Literature

REVIEW OF LITERATURE

Project No. E-20-G03 (R6144-0A0)
Criteria for Two-Way Left-Turn Lanes
Versus Other Median Treatments
Task Order No. 6 Under BOA No. 90 Dated
1/9/84

Prepared by Georgia Tech, Civil Engineering for Georgia DOT
August, 1986

Over the thirty years since the first Two-Way Left-Turn Lane (TWLTL) was installed considerable research on the TWLTL's operating characteristics has been done. Around the time of the installation of the first TWLTL, highway engineers had been removing bi-directional passing lanes because of very high head-on collision rates. Consequently, many engineers were reluctant to use another road configuration involving a lane used by vehicles traveling in both directions.

Because of the accident problems experienced by the bi-directional passing lanes, TWLTLs were opposed by traffic engineers who felt that TWLTLs would have similarly high head-on accident rates. As a consequence, early TWLTL studies concentrated on two major points: improper (i.e., potentially dangerous) use of TWLTL's and the comparison of before-TWLTL and after-TWLTL accident rates. Typically, head-on collision rates were studied to see if they increased after TWLTL installation. Even though an early study on TWLTL operation showed that head-on collisions were an uncommon occurrence and of little concern (1), later studies included head-on collisions as part of their accident analysis.

During the late 1960s the increase in commercial strip

development in the form of fast-food restaurants and shopping centers produced a need for some traffic engineering technique which could handle the increased midblock left-turn volume. The TWLTL was seen as an safe and effective way to handle midblock left turns. As TWLTL use increased, so did the desire to learn more about its operating characteristics. Two projects conducted during the mid-1970's addressed TWLTL operating characteristics.

Nemeth's research at the Ohio State University (2) specifically focused on the operating characteristics of TWLTLs, and also included a literature review summarizing previous TWLTL research. The other major research concerning median treatments was performed by Glennon for the FHWA in 1975 (3). Glennon's results allowed the user to determine the optimum median treatment, given the ADT and level of roadside development of a certain road. would determine the optimum median treatment.

Since the mid-1970's TWLTLs have continued to be the focus of much research. In 1979, Parker used regression equations to determine the best type of median treatment based on ADT and accident rates (4). Other recent research has used computer simulation in an effort to simulate arterial operation (5, 6, 7).

In an effort to organize a TWLTL and median treatment based literature review, the literature will be grouped as follows: 1) Accident Research, 2) Operational

Characteristics, 3) Volume/Capacity Research, 4) Computer Simulation, 5) Comparison of TWLTLs with Other Median Treatments, and 6) Other Relevant Literature.

ACCIDENT RESEARCH

Accident-oriented research forms a large part of the TWLTL body of knowledge for two major reasons: accident reports are easy to find for statistical analysis also, early opponents of TWLTLs used high accident rates as a defense against TWLTL use. Accident research usually focused on one of two basic methodologies: comparison of accident rates before and after the installation of a TWLTL, or determination of TWLTL effectiveness based on benefit-cost ratios.

Accident Rate Reduction Research

The results of Glennon's mid-1970's research (8) was presented in terms of the estimated annual accident reduction per mile for different median treatments (including TWLTLs and raised medians). The input factors were the level of roadside development and the highway ADT. The preferred median treatment was chosen on the basis of accident reduction. In the case of a combination of a high ADT and a high level of roadside development (>60 driveways per mile), a raised median showed a greater reduction in accident rates (compared to no median treatment) than a TWLTL showed.

Glennon states that a TWLTL is preferrable only where no other median type is possible. Glennon's criteria recommended a TWLTL for the following combination of ADT and driveway density: 10,000-20,000 ADT, more than 60 driveways per mile, less than 10 high-volume driveways/mile, speeds greater than 30 mph and the left-turn volume per mile should equal 20% of the peak hour volume. These combinations of volume and development imply that TWLTLs are best used on roads with high levels of development, but with moderate levels of traffic.

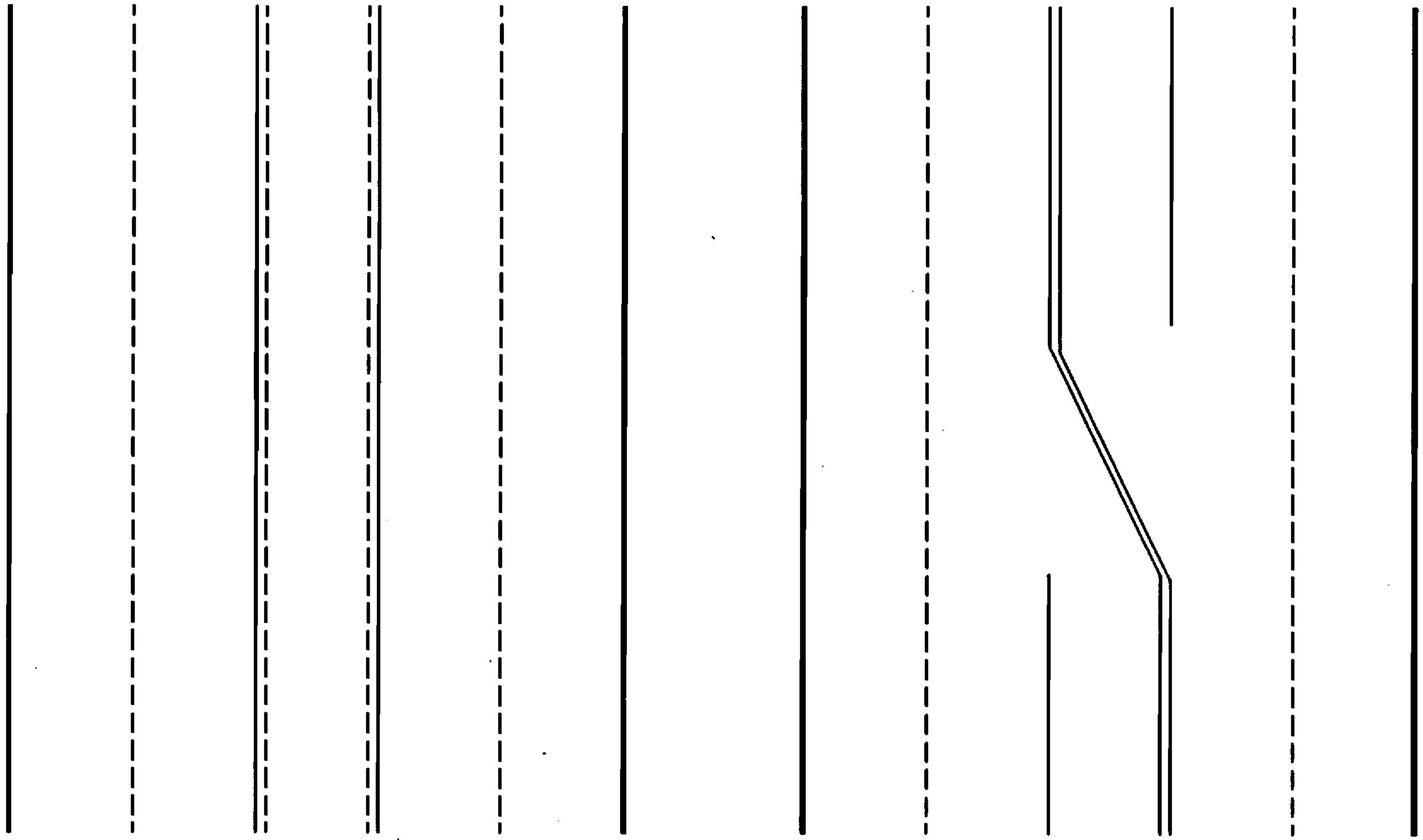
Hoffman's defense of TWLTLs (9) presented results of studies performed on four Michigan arterials that compared the accident rates before and after the installation of TWLTLs. Total accidents were reduced by about 33%, head-on collisions by 45% and rear-end accidents by 62%. Hoffman recognized the existance of a "limit" on the volume which a facility with a TWLTL could handle efficiently. At this "limit," Hoffman states that the road begins to function more like a typical four-lane highway (without a TWLTL). Hoffman continues by stating that TWLTL efficiency is increased by careful planning of driveway locations so that queues of left-turning vehicles will not overlap and cause delay for both through and left-turning vehicles.

Another report (10) uses observed conflicts as a surrogate for accidents. Three different roadway sections were analyzed based on the number of conflicts

observed on each section. The TWLTL was found to have a lower conflict rate than the other sections analyzed (one with no left-turn provision and another with an alternating left-turn lane (figure 1). The conflict analysis was performed on sections having a total of four through lanes with ADT between 10,000 and 20,000. Nemeth (11) used a similar technique by measuring the number of "erratic maneuvers" (brakings and weavings) observed on highways before and after the installation of a TWLTL. Running speeds were also used as a measure of effectiveness. Nemeth found that both measures of effectiveness changed favorably for a road which had a TWLTL installed with no corresponding loss of through lanes.

Parker's research (12) also involved accident research but resulted instead in a set of regression equations which had four input variables: ADT, streets and signals per mile, local population and driveways per mile. From this input two equations were ultimately solved: one would give the preferred median treatment based on accident data, and the other would state the preferred treatment based on delay estimates.

Perhaps the most recent research of this type was performed by Harwood (13). His comparison of different types of arterials used 8 independent variables: ADT, truck percentage, type of development, estimated level of left-turn demand, shoulder width, speed, driveways per



TWO-WAY LEFT-TURN LANE   ALTERNATING LEFT-TURN LANE

FIGURE 1 - DIFFERENT TYPES OF LEFT-TURN LANES

mile, and unsignalized intersections per mile. A statistical analysis of the difference in accident rates between different arterial designs was conducted. Analyses of covariance for nonintersection and unsignalized intersection accident rates was done in an effort to determine factors relevant to accident rates. Unfortunately, the groupings for ADT extended up to 20,000, with one category for ADTs "over 20,000" to cover high-volume arterials.

Another study (14) states that TWLTLs reduce accident rates by approximately 35 percent when installed at urban and suburban sites on multilane highways. This is in comparison with the "before" TWLTL condition.

A recent Public Roads article (15) discusses accident rates on arterials featuring reversable-flow and TWLTLs. The article centered on drivers' understanding of signage for this unusual arrangement of lanes, and that bearing on accident rates.

Benefit-Cost Ratio Research

Accident-oriented research using benefit-cost ratios as criteria were often presented as an extension of the accident-rate reduction research so as to justify a certain median treatment on the basis of the benefit-cost ratio of the improvement. As it is with any accident-oriented research, the major difficulty associated with benefit-cost ratios is the difficulty of estimating the cost of the "typical" accident. It is not terribly

difficult to determine the average cost of a property damage only accident; placing a "price on someone's head" is an entirely different matter. The difficulty in determining human worth is a good reason why much accident-oriented research stops after it states the potential reduction in accidents associated with a given median treatment; it is left to the engineer using the results to translate that reduction into a "dollars and cents" quantity.

Glennon and Harwood's research (16) adopted this method in analyzing the choice of median treatments. The final results took into consideration ADT and the level of development along the arterial and presented the results in a tabulated form. Their results showed that a TWLTL was preferred even for high levels of ADT and roadside development. This result implies no limit on the traffic volumes for efficient TWLTL operation.

Several potential problems exist with Glennon and Harwood's techniques and the authors address them. The benefit data was based on vehicular delay and accident reduction data, and the accident reduction data was based on regression equations, which are not necessarily accurate predictors of real-world activity. Also of concern is that the cost information was based on 1974 data and must be adjusted to compensate for inflation.

Benefit-cost ratios typically favor TWLTLs since the initial construction cost is low with respect to other

median treatments (raised or depressed medians, for instance). TWLTLs can be constructed on relatively narrow right-of-way. In some situations, TWLTLs can be created by restriping a 2- or 4-lane highway with little or no widening.

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The state of Washington uses TWLTLs on multilane roads with ADT between 10,000 and 25,000 and on two-lane roads between 5,000 and 12,500 (28). Their upper limit of 25,000 ADT is echoed by Thompson (29) for a five-lane road. Thompson goes on to state that 40,000 ADT exceeds the practical capacity of a seven-lane road, which he concludes on the basis of observing a seven-lane road with 40,000 ADT in Grand Rapids.

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Both the old and new Capacity Manuals address the capacity characteristics of roads with various median treatments. One states that because a raised median reduces the "friction" between opposing directions of traffic, a road with a raised median will have a higher capacity than a five-lane road (31). While the new Capacity Manual (32) recognizes that midblock congestion

can be the limiting capacity factor, it states no method for midblock capacity determination. Elsewhere, the new manual states that a road with a TWLTL will operate somewhere inbetween an undivided and a divided road. The "Adjustment Factor for Type of Multilane Highway and Development Environment" is an attempt to quantify the effects of roadside development and median treatments in the calculation of highway capacity. This factor is determined subjectively and has no numerical guidelines. Harwood's recent research on median alternatives (33) states the preferred condition for TWLTLs: low to moderate through volumes, high left-turn volumes, high driveway densities and high rear-end and right-angle accident rates. He states that delay reduction (compared with no TWLTL) is modest at low volume levels and large at large flow rates. He also states that little work has been done to establish volume ranges for the installation of TWLTLs.

COMPUTER SIMULATION

Since the mid-1970's computer simulation of arterial operation has been a popular method to model operating characteristics under a variety of conditions. Heikal developed the ARTSIM program (34) to model arterial flow at varying levels of through volume, left-turn volume, and roadside development. The level-of-service concept

propsed by Heikal is based on the friction between left-turning vehicles and through vehicles and is measured in the average number of stops per vehicle. ARTSIM was developed to compare the quality of arterial flow with and without a TWLTL, and it could be used to model TWLTLs under a variety of circumstances as well as boulevard-type arterial design.

Similarly, McCoy (35) used the General Purpose Simulation System (GPSS) language to simulate the operation of a three-lane facility. GPSS allows the user to specify different volumes and driveway densities. McCoy used the reduction in stops and delay as his measures of effectiveness.

The NETSIM computer program was proposed for the determination of the quality of urban arterial flow (36). It involved considerable data collection with respect to the geometrics of the arterial. Careful data collection would ultimately provide a realistic computer model. Although specific references to TWLTLs were not made, NETSIM could be easily adapted to research aimed at quantifying the operating characteristics of urban arterials with TWLTLs.

McCoy's latest simulation work, TWLTL-SIM, written with GPSS was written to simulate a 5-lane section with TWLTL. Using Gerlough and Wagner's gap acceptance function, he determined the probability of a vehicle's accepting a certain gap to determine the needed gap for making a left

turn. Unfortunately, the model is designed to abort left turns when those turns cause a jammed flow situation (37).

COMPARISON OF TWLTLS WITH OTHER MEDIAN TREATMENTS

Some literature concentrates on comparing TWLTLs with other median treatments (raised or depressed medians, typically). While some of this literature is presented as results of research, much of it is presented in the form of survey results or personal comments.

Survey Results

The surveys summarized here were surveys of public highway engineers by various technical committees. One survey (38) addresses TWLTL experience directly. Questions that were asked included the amount of experience respondants had with TWLTLs, how many miles of TWLTL were in their jurisdiction and more subjective questions concerning observed operating characteristics. The survey also asked if respondants felt TWLTLs statistically improve arterial operation by reducing or accident rates, improved travel speeds, etc.

Another survey was directed toward engineers having experience with TWLTLs and median acceleration lanes (MALs). MALs are used at T-intersections, typically, in order to provide acceleration room for vehicles turning left from the stem of the T. TWLTLs were favored by most

respondants. The concluding comments recognized that "more research is needed to develop guidelines [for] the appropriate . . . median treatment for site specific roadway and traffic conditions" (39).

Design Guidelines

The new AASHTO "Green Book" (40) gives generalized comments on techniques to provide for excessive left-turning volumes. Summing up, the Green Book states that any type of access control should meet four basic criteria: it should 1) limit the number of conflict points, 2) separate basic conflict areas, 3) reduce maximum deceleration requirements, and 4) remove turning vehicles from through lanes.

The Federal Highway Administration recommends TWLTLs as a design alternative which provides safe deceleration and storage areas for left-turning vehicles. TWLTLs are also recommended because midblock locations on arterials have the potential to limit capacity because of excessive left-turning movements. In addition, TWLTLs contribute to the flexibility of a road, since they can also be used as HOV or reversible flow lanes during peak periods. Other median treatments are presented as being advantageous for the reduction of accidents due to vehicle cross-overs and quick stops by left-turning vehicles. Very high concentrations of vehicles at median openings could contribute to degradation of flow, however (41).

ITE's Guidelines discuss TWLTLs and medians separately. TWLTLs are recommended as alternatives for situations withhigh commercial development and narrow right-of-way. The "preferred" median treatment, however, involves an unspecified type of median with provisions for left turns at intervals. The provisions for left turns may be as conventional as a left-turn lane cut into the median or it could be an indirect left turn (jughandle or cloverleaf) (42).

One of the earlier studies on median treatments (43) ignores the subject of TWLTLs completely. The theory proposed by this study is that access to abutting land uses should be restricted as much as possible with left turns permitted at median openings or at intersections. Sufficient right-of-way was recognized as being necessary for adequate U-turning radius.

OTHER RELEVANT LITERATURE

While the following literature is not directly related to TWLTLs, it presents concepts essential to the determination of the characteristics of left-turning vehicles

Left-Turn Lane Literature

Kenneth Agent's left-turn lane warrants (44) were based on delay (maximum of 30 seconds per vehicle), load factor (0.3 is critical), accidents (maximum of four per year at

unsignalized intersections, or five per year at signalized intersections) and traffic conflicts. NETSIM was used to develop relationships between left-turn percentage, total volume and cycle split.

The SOAP 84 User's Manual provides a model for the calculation of the capacity of unprotected left-turn intervals at signalized intersections (45). This model could be used to determine the capacity of an unprotected mid-block left-turn interval since similar conditions exist at mid-block with the exception of the traffic signal.

<u>Capacity Literature</u>

The capacity-oriented literature reviewed outlines relatively simple methods for determining the capacity of a road. Dudek (46), in an effort to determine freeway capacity where one or two lanes was closed for construction, used 30 minute counts. Apparently, these counts were performed during peak periods since the capacity of the facility was determined from the highest of these counts.

Another report (47) used similar techniques but used 2 minute counts to better capture the peaking characteristics of freeway flow. Histograms were plotted of the flow rate versus the time of day. The capacity was then determined by looking at the highest flow rate (which occured during the morning peak). The authors complained that the term "capacity" was in need of

clarification, since they felt that capacity needed to be maintained for a specific length of time.

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Appendix B

Review of Literature

REVIEW OF LITERATURE

Project No. E-20-G03 (R6144-0A0)
Criteria for Two-Way Left-Turn Lanes
Versus Other Median Treatments
Task Order No. 6 Under BOA No. 90 Dated
1/9/84

Prepared by Georgia Tech, Civil Engineering for Georgia DOT
August, 1986

Over the thirty years since the first Two-Way Left-Turn Lane (TWLTL) was installed considerable research on the TWLTL's operating characteristics has been done. Around the time of the installation of the first TWLTL, highway engineers had been removing bi-directional passing lanes because of very high head-on collision rates. Consequently, many engineers were reluctant to use another road configuration involving a lane used by vehicles traveling in both directions.

Because of the accident problems experienced by the bi-directional passing lanes, TWLTLs were opposed by traffic engineers who felt that TWLTLs would have similarly high head-on accident rates. As a consequence, early TWLTL studies concentrated on two major points: improper (i.e., potentially dangerous) use of TWLTL's and the comparison of before-TWLTL and after-TWLTL accident rates. Typically, head-on collision rates were studied to see if they increased after TWLTL installation. Even though an early study on TWLTL operation showed that head-on collisions were an uncommon occurrence and of little concern (1), later studies included head-on collisions as part of their accident analysis.

During the late 1960s the increase in commercial strip

development in the form of fast-food restaurants and shopping centers produced a need for some traffic engineering technique which could handle the increased midblock left-turn volume. The TWLTL was seen as an safe and effective way to handle midblock left turns. As TWLTL use increased, so did the desire to learn more about its operating characteristics. Two projects conducted during the mid-1970's addressed TWLTL operating characteristics.

Nemeth's research at the Ohio State University (2) specifically focused on the operating characteristics of TWLTLs, and also included a literature review summarizing previous TWLTL research. The other major research concerning median treatments was performed by Glennon for the FHWA in 1975 (3). Glennon's results allowed the user to determine the optimum median treatment, given the ADT and level of roadside development of a certain road. would determine the optimum median treatment.

Since the mid-1970's TWLTLs have continued to be the focus of much research. In 1979, Parker used regression equations to determine the best type of median treatment based on ADT and accident rates (4). Other recent research has used computer simulation in an effort to simulate arterial operation (5, 6, 7).

In an effort to organize a TWLTL and median treatment based literature review, the literature will be grouped as follows: 1) Accident Research, 2) Operational

Characteristics, 3) Volume/Capacity Research, 4) Computer Simulation, 5) Comparison of TWLTLs with Other Median Treatments, and 6) Other Relevant Literature.

ACCIDENT RESEARCH

Accident-oriented research forms a large part of the TWLTL body of knowledge for two major reasons: accident reports are easy to find for statistical analysis also, early opponents of TWLTLs used high accident rates as a defense against TWLTL use. Accident research usually focused on one of two basic methodologies: comparison of accident rates before and after the installation of a TWLTL, or determination of TWLTL effectiveness based on benefit-cost ratios.

Accident Rate Reduction Research

The results of Glennon's mid-1970's research (8) was presented in terms of the estimated annual accident reduction per mile for different median treatments (including TWLTLs and raised medians). The input factors were the level of roadside development and the highway ADT. The preferred median treatment was chosen on the basis of accident reduction. In the case of a combination of a high ADT and a high level of roadside development (>60 driveways per mile), a raised median showed a greater reduction in accident rates (compared to no median treatment) than a TWLTL showed.

Glennon states that a TWLTL is preferrable only where no other median type is possible. Glennon's criteria recommended a TWLTL for the following combination of ADT and driveway density: 10,000-20,000 ADT, more than 60 driveways per mile, less than 10 high-volume driveways/mile, speeds greater than 30 mph and the left-turn volume per mile should equal 20% of the peak hour volume. These combinations of volume and development imply that TWLTLs are best used on roads with high levels of development, but with moderate levels of traffic.

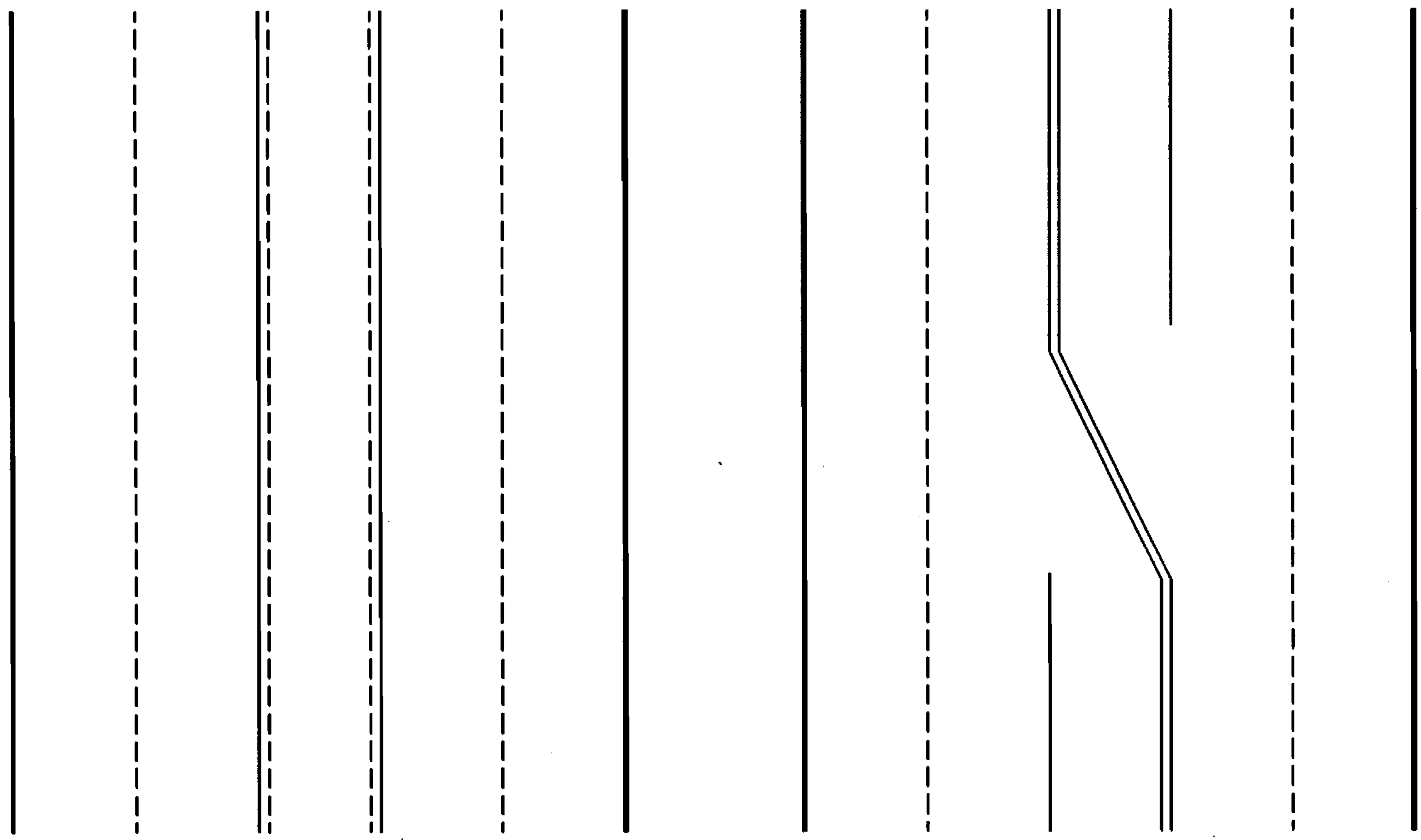
Hoffman's defense of TWLTLs (9) presented results of studies performed on four Michigan arterials that compared the accident rates before and after the installation of TWLTLs. Total accidents were reduced by about 33%, head-on collisions by 45% and rear-end accidents by 62%. Hoffman recognized the existance of a "limit" on the volume which a facility with a TWLTL could handle efficiently. At this "limit," Hoffman states that the road begins to function more like a typical four-lane highway (without a TWLTL). Hoffman continues by stating that TWLTL efficiency is increased by careful planning of driveway locations so that queues of left-turning vehicles will not overlap and cause delay for both through and left-turning vehicles.

Another report (10) uses observed conflicts as a surrogate for accidents. Three different roadway sections were analyzed based on the number of conflicts

observed on each section. The TWLTL was found to have a lower conflict rate than the other sections analyzed (one with no left-turn provision and another with an alternating left-turn lane (figure 1). The conflict analysis was performed on sections having a total of four through lanes with ADT between 10,000 and 20,000. Nemeth (11) used a similar technique by measuring the number of "erratic maneuvers" (brakings and weavings) observed on highways before and after the installation of a TWLTL. Running speeds were also used as a measure of effectiveness. Nemeth found that both measures of effectiveness changed favorably for a road which had a TWLTL installed with no corresponding loss of through lanes.

Parker's research (12) also involved accident research but resulted instead in a set of regression equations which had four input variables: ADT, streets and signals per mile, local population and driveways per mile. From this input two equations were ultimately solved: one would give the preferred median treatment based on accident data, and the other would state the preferred treatment based on delay estimates.

Perhaps the most recent research of this type was performed by Harwood (13). His comparison of different types of arterials used 8 independent variables: ADT, truck percentage, type of development, estimated level of left-turn demand, shoulder width, speed, driveways per



TWO-WAY LEFT-TURN LANE

ALTERNATING LEFT-TURN LANE

FIGURE 1 - DIFFERENT TYPES OF LEFT-TURN LANES

mile, and unsignalized intersections per mile. A statistical analysis of the difference in accident rates between different arterial designs was conducted. Analyses of covariance for nonintersection and unsignalized intersection accident rates was done in an effort to determine factors relevant to accident rates. Unfortunately, the groupings for ADT extended up to 20,000, with one category for ADTs "over 20,000" to cover high-volume arterials.

Another study (14) states that TWLTLs reduce accident rates by approximately 35 percent when installed at urban and suburban sites on multilane highways. This is in comparison with the "before" TWLTL condition.

A recent Public Roads article (15) discusses accident rates on arterials featuring reversable-flow and TWLTLs. The article centered on drivers' understanding of signage for this unusual arrangement of lanes, and that bearing on accident rates.

Benefit-Cost Ratio Research

Accident-oriented research using benefit-cost ratios as criteria were often presented as an extension of the accident-rate reduction research so as to justify a certain median treatment on the basis of the benefit-cost ratio of the improvement. As it is with any accident-oriented research, the major difficulty associated with benefit-cost ratios is the difficulty of estimating the cost of the "typical" accident. It is not terribly

difficult to determine the average cost of a property damage only accident; placing a "price on someone's head" is an entirely different matter. The difficulty in determining human worth is a good reason why much accident-oriented research stops after it states the potential reduction in accidents associated with a given median treatment; it is left to the engineer using the results to translate that reduction into a "dollars and cents" quantity.

Glennon and Harwood's research (16) adopted this method in analyzing the choice of median treatments. The final results took into consideration ADT and the level of development along the arterial and presented the results in a tabulated form. Their results showed that a TWLTL was preferred even for high levels of ADT and roadside development. This result implies no limit on the traffic volumes for efficient TWLTL operation.

Several potential problems exist with Glennon and Harwood's techniques and the authors address them. The benefit data was based on vehicular delay and accident reduction data, and the accident reduction data was based on regression equations, which are not necessarily accurate predictors of real-world activity. Also of concern is that the cost information was based on 1974 data and must be adjusted to compensate for inflation.

Benefit-cost ratios typically favor TWLTLs since the initial construction cost is low with respect to other

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Sawhill and Hall state that "traffic volumes as such are not always found to be a warrant, but volumes approaching roadway capacities in either direction may be a reason for not installing the TWLTL, more important would be the observations of time gaps or sufficient length for left turn movements to be accomplished." (30).

Both the old and new Capacity Manuals address the capacity characteristics of roads with various median treatments. One states that because a raised median reduces the "friction" between opposing directions of traffic, a road with a raised median will have a higher capacity than a five-lane road (31). While the new Capacity Manual (32) recognizes that midblock congestion

can be the limiting capacity factor, it states no method for midblock capacity determination. Elsewhere, the new manual states that a road with a TWLTL will operate somewhere inbetween an undivided and a divided road. The "Adjustment Factor for Type of Multilane Highway and Development Environment" is an attempt to quantify the effects of roadside development and median treatments in the calculation of highway capacity. This factor is determined subjectively and has no numerical guidelines. Harwood's recent research on median alternatives (33) states the preferred condition for TWLTLs: low to moderate through volumes, high left-turn volumes, high driveway densities and high rear-end and right-angle accident rates. He states that delay reduction (compared with no TWLTL) is modest at low volume levels and large at large flow rates. He also states that little work has been done to establish volume ranges for the installation of TWLTLs.

COMPUTER SIMULATION

Since the mid-1970's computer simulation of arterial operation has been a popular method to model operating characteristics under a variety of conditions. Heikal developed the ARTSIM program (34) to model arterial flow at varying levels of through volume, left-turn volume, and roadside development. The level-of-service concept

propsed by Heikal is based on the friction between left-turning vehicles and through vehicles and is measured in the average number of stops per vehicle. ARTSIM was developed to compare the quality of arterial flow with and without a TWLTL, and it could be used to model TWLTLs under a variety of circumstances as well as boulevard-type arterial design.

Similarly, McCoy (35) used the General Purpose Simulation System (GPSS) language to simulate the operation of a three-lane facility. GPSS allows the user to specify different volumes and driveway densities. McCoy used the reduction in stops and delay as his measures of effectiveness.

The NETSIM computer program was proposed for the determination of the quality of urban arterial flow (36). It involved considerable data collection with respect to the geometrics of the arterial. Careful data collection would ultimately provide a realistic computer model. Although specific references to TWLTLs were not made, NETSIM could be easily adapted to research aimed at quantifying the operating characteristics of urban arterials with TWLTLs.

McCoy's latest simulation work, TWLTL-SIM, written with GPSS was written to simulate a 5-lane section with TWLTL. Using Gerlough and Wagner's gap acceptance function, he determined the probability of a vehicle's accepting a certain gap to determine the needed gap for making a left

turn. Unfortunately, the model is designed to abort left turns when those turns cause a jammed flow situation (37).

COMPARISON OF TWLTLS WITH OTHER MEDIAN TREATMENTS

Some literature concentrates on comparing TWLTLs with other median treatments (raised or depressed medians, typically). While some of this literature is presented as results of research, much of it is presented in the form of survey results or personal comments.

Survey Results

The surveys summarized here were surveys of public highway engineers by various technical committees. One survey (38) addresses TWLTL experience directly. Questions that were asked included the amount of experience respondants had with TWLTLs, how many miles of TWLTL were in their jurisdiction and more subjective questions concerning observed operating characteristics. The survey also asked if respondants felt TWLTLs statistically improve arterial operation by reducing or accident rates, improved travel speeds, etc.

Another survey was directed toward engineers having experience with TWLTLs and median acceleration lanes (MALs). MALs are used at T-intersections, typically, in order to provide acceleration room for vehicles turning left from the stem of the T. TWLTLs were favored by most

respondants. The concluding comments recognized that "more research is needed to develop guidelines [for] the appropriate . . . median treatment for site specific roadway and traffic conditions" (39).

Design Guidelines

The new AASHTO "Green Book" (40) gives generalized comments on techniques to provide for excessive left-turning volumes. Summing up, the Green Book states that any type of access control should meet four basic criteria: it should 1) limit the number of conflict points, 2) separate basic conflict areas, 3) reduce maximum deceleration requirements, and 4) remove turning vehicles from through lanes.

The Federal Highway Administration recommends TWLTLs as a design alternative which provides safe deceleration and storage areas for left-turning vehicles. TWLTLs are also recommended because midblock locations on arterials have the potential to limit capacity because of excessive left-turning movements. In addition, TWLTLs contribute to the flexibility of a road, since they can also be used as HOV or reversible flow lanes during peak periods. Other median treatments are presented as being advantageous for the reduction of accidents due to vehicle cross-overs and quick stops by left-turning vehicles. Very high concentrations of vehicles at median openings could contribute to degradation of flow, however (41).

ITE's Guidelines discuss TWLTLs and medians separately. TWLTLs are recommended as alternatives for situations withhigh commercial development and narrow right-of-way. The "preferred" median treatment, however, involves an unspecified type of median with provisions for left turns at intervals. The provisions for left turns may be as conventional as a left-turn lane cut into the median or it could be an indirect left turn (jughandle or cloverleaf) (42).

One of the earlier studies on median treatments (43) ignores the subject of TWLTLs completely. The theory proposed by this study is that access to abutting land uses should be restricted as much as possible with left turns permitted at median openings or at intersections. Sufficient right-of-way was recognized as being necessary for adequate U-turning radius.

OTHER RELEVANT LITERATURE

While the following literature is not directly related to TWLTLs, it presents concepts essential to the determination of the characteristics of left-turning vehicles

Left-Turn Lane Literature

Kenneth Agent's left-turn lane warrants (44) were based on delay (maximum of 30 seconds per vehicle), load factor (0.3 is critical), accidents (maximum of four per year at

unsignalized intersections, or five per year at signalized intersections) and traffic conflicts. NETSIM was used to develop relationships between left-turn percentage, total volume and cycle split.

The SOAP 84 User's Manual provides a model for the calculation of the capacity of unprotected left-turn intervals at signalized intersections (45). This model could be used to determine the capacity of an unprotected mid-block left-turn interval since similar conditions exist at mid-block with the exception of the traffic signal.

Capacity Literature

The capacity-oriented literature reviewed outlines relatively simple methods for determining the capacity of a road. Dudek (46), in an effort to determine freeway capacity where one or two lanes was closed for construction, used 30 minute counts. Apparently, these counts were performed during peak periods since the capacity of the facility was determined from the highest of these counts.

Another report (47) used similar techniques but used 2 minute counts to better capture the peaking characteristics of freeway flow. Histograms were plotted of the flow rate versus the time of day. The capacity was then determined by looking at the highest flow rate (which occured during the morning peak). The authors complained that the term "capacity" was in need of

clarification, since they felt that capacity needed to be maintained for a specific length of time.

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Appendix C

Annotated Bibliography

GDOT Res. Proj. 8602

ANNOTATED BIBLIOGRAPHY

Project No. E-20-G03 (R6144-OAO)
Criteria for Two-Way Left-Turn Lanes
Versus Other Median Treatments
Task Order No. 6 Under BOA No. 90 Dated 11/9/84
Prepared by Georgia Tech, Civil Engineering for Georgia DOT
August, 1986

Agent, Kenneth R., "Warrants For Left-Turn Lanes," Transportation Quarterly, Vol. 37, No. 1, January 1983, Westport, Connecticut, pp. 99-114.

The purpose of this report was to develop numerical criteria for the installation of a left-turn lane. Agent cites the fact that few states use numerical warrants for left-turn lane installation. Most states do have some form of guidelines, however, usually based on accidents, volume or delay. The paper presents warrants based on these three parameters.

Agent chooses 30 seconds of delay as excessive for a signalized intersection. 0.3 is the critical load factor chosen for volume warrants, and four (unsignalized) or five (signalized) left-turn accidents in one year is also a warrant for a left-turn lane. These criteria were analyzed using NETSIM, and relationships between left-turn percentage, total main street volume, and cycle split were derived to determine the volume warrant. Delay per vehicle, percent left turns and opposing volume were used to determine the delay warrant criteria. A warrant is also provided for traffic conflicts: an average of 30 or more total left-turn related conflicts or 6 or more opposing left-turn conflicts in a 3-hour study period during peak conditions.

American Association of State Highway and Transportation Officials, A Policy on Geometric Design of Highways and Streets, 1984, Washington, p. 109-110.

Information given by this document is general, directing the reader to other documents and providing general guidelines concerning access control, with the major emphasis being safety improvement of existing highways. The purpose of access control is to reduce the interference with through traffic by other vehicles or pedestrians entering, leaving, and crossing the highway. On streets or highways where there is no control of access and roadside businesses develop, interference from the roadside can become a major factor in reducing the capacity, increasing the accident potential and eroding the mobility function that the facility was designed to provide. If access points are numerous and entering and exiting volumes are heavy, the capacity and safety of the facility are reduced. Any form of access control should meet these four major criteria: limit the number of conflict points, separate basic conflict areas, reduce maximum deceleration requirements and remove turning vehicles from the through lanes.

Dale, Charles W., "Procedure for Evaluating Traffic Engineering Improvements," ITE Journal, April 1981, pp. 39-46.

This article outlines procedures for evaluating low-capital improvements. Most of the measures of effectiveness are user-oriented, such as user cost, travel time, and fuel consumption. The author suggests that volume data be obtained from local planning organizations, but mentions nothing about determining the capacity of existing highways.

Dudek, Conrad L., and Stephen H. Richards, "Traffic Capacity Through Urban Freeway Work Zones in Texas," Transportation Research Record 869, Washington, 1982, pp. 14-18.

This report dealt with the problem of determining the capacity of a freeway section which had one or more through lanes closed for construction work. The authors determined the capacity of the remaining open lanes by counting cars over a 30-minute period (presumably the peak period), converting that to an equivalent flow rate, and calling that the capacity. It was not stated when these counts were made.

Federal Highway Administration, "Design of Urban Streets," Student Textbook, prepared by JHK & Associates for the United States Department of Transportation, Washington, September, 1977, pp. 6-6, 7-12, 7-14.

Midblock techniques for maximizing capacity are discussed, as "midblock sections may experience significant amounts of traffic interruption, primarily due to access/egress movements." TWLTLs provide safe deceleration and storage areas for vehicles turning left, reducing delay and disturbances to the overall traffic flow. they can be used as a reversible lane or an HOV lane during peak periods.

Nemeth's report of July, 1976 is referenced. The 1972 Michigan study of four arterials converted to TWLTL (Two-Way Left-Turn Lane) operation is quoted, including the 33 percent reduction in total accidents. However, high speeds combined with rolling terrain is hazardous. Also, if the number of movements made in the lane becomes too large there will be an increase in accidents or near accidents.

The textbook briefly discusses the advantages and disadvantages of physical (raised) medians of various widths, and three kinds of painted medians. Raised medians at least four feet wide can provide pedestrian refuge, and a pushbutton can be installed on the median to increase the efficiency of main-street flow. They can reduce accidents due to vehicle cross-overs and sudden stops by left-turning vehicles. However, turns from or to cross streets may become overconcentrarted at median openings and U-turns may become a problem at these points.

Fisher, John E., letter to Mark R. Norman of May 14, 1985, city of Los Angeles traffic engineer.

Mr. Fisher mentions in his letter that he has extensive experience with seven lane highways, several with ADT in excess of 40,000 vehicles in the Los Angeles area. Most of these highways have right-of-way usually less than 100 feet. He describes the operation on these streets as satisfactory at best. He does not recommend a seven lane section as a standard, preferring a divided section with left-turn bays at intervals.

Georgia Division, Southern Section, Institute of Traffic Engineers, "Report of a Study of Two-Way Left-Turn Lanes".

This report was cited by Nemeth, who quoted the Georgia Division as recommending TWLTL use on five-lane roads with ADTs between 10,000 and 25,000. Three-lane sections were recommended for ADTs below 10,000. This paper also concluded that the benefits of a TWLTL (lower accident rates, lower left-turn vehicular delay, lower through-vehicle delay) became questionable as the volumes approach capacity due to the lack of gaps in opposing traffic needed to make left turns.

Glennon, J.C., et. al., "Evaluation of Techniques for the Control of Direct Access to Arterial Highways," Report No. FHWA-RD-76-87, Federal Highway Administration, Washington, August, 1975.

Glennon et al. found that the TWLTL is inferior to the raised median where frequent driveways are in combination with high arterial street volumes. A TWLTL is a more effective accident reduction technique at lower levels roadside development and traffic volumes as reflected in the tabulation below:

Level of Roadside Development (driveways per mile)	Highway ADT	Estimated Annual Accident Reduction Per Mile: Raised Median	Continuous TWLTL
Low (<30)	Low (<5,000)	2.2	4.4
High (>60)	High (>15,000)	31.2	28.6

Glennon suggested that a TWLTL be employed only where conventional raised or flush medians are not practical. He recommended that a TWLTL be warranted when ADT reaches 10,000 to 20,000 vpd, level of development exceeds 60 driveways per mile, fewer than 10 high-volume driveways per mile, speeds >30 mph. Also, left-turning driveway maneuvers per mile should total at least 20% of the traffic volume during peak periods.

City of Grand Rapids, Michigan, The 28th Street Corridor Project, 1981.

This report was written to suggest a solution to congestion because of high mid-block left turns and the associated accident rate. 28th Street is a five-lane facility with 40-50,000 ADT. Recommended improvements included raised medians with left turn pockets at intervals and consolidation of signs to abutting businesses. Also recommended were aesthetic improvements to improve the motorists' ability to take in the businesses abutting the street.

Harwood, Douglas W., "Multilane Design Alternatives for Improving Suburban Highways", NCHRP Report 282, Transportation Research Board, Washington, D.C., 1986, pp. 27-59.

Like Parker (1979), Harwood developed regression equations to estimate accidents. This work seems to be the most recent of this type. Harwood's comparison of different types of arterials used 8 independent variables: ADT, truck percentage, type of development, estimated level of left-turn demand, shoulder width, speed, driveways per mile, and unsignalized intersections per mile. A statistical analysis of the difference in accident rates between different arterial designs was conducted. Analyses of covariance for nonintersection and unsignalized intersection accident rates was done in an effort to determine factors relevant to accident rates. Unfortunately, the groupings for ADT extended up to 20,000, with one category for ADTs "over 20,000" to cover high-volume arterials. Harwood's conclusions relating to accidents can be summarized only by reprinting five tables:

Table 1. Average accident rates for nonintersection accidents on suburban arterial highways.

BASIC ACCIDENT RATES
(accidents per million vehicle-miles)

Type of Development	Design Alternative 2U	3T	4U	4D	5T
Commercial	2.39	1.56	2.85	2.90	2.69
Residential	1.88	1.64	0.97	1.39	1.39

ADJUSTMENT FACTORS

	Under 30	30-60	Over 60
Driveways per mile	-0.41	-0.03	+0.35

	Under 5%	5-10%	Over 10%
Truck percentage	+0.18	-0.07	-0.33

Note: Accident rates should be decreased by 5% for highway sections with full shoulders and increased by 5% for highway sections with no shoulders.

Table 2. Average accident rates for unsignalized intersection accidents on suburban arterial highways.

BASIC ACCIDENT RATES
(accidents per million vehicle-miles)

Type of Development	Design Alternative 2U	3T	4U	4D	5T
Commercial	2.11	2.43	4.77	4.71	3.11
Residential	2.88	1.91	3.03	2.71	1.85

ADJUSTMENT FACTORS

	Under 5	5-10	Over 10
Intersections per mile	-0.99	+0.28	+1.55

	Under 5%	5-10%	Over 10%
Truck percentage	+0.22	-0.08	-0.38

Table 3. Total accident rates for suburban arterial highways (including nonintersection and unsignalized intersection accidents).

BASIC ACCIDENT RATES
(accidents per million vehicle-miles)

Type of Development	Design Alternative 2U	3T	4U	4D	5T
Commercial	4.50	3.99	7.62	7.61	5.80
Residential	4.76	3.55	4.00	4.10	3.24

ADJUSTMENT FACTORS

	Under 30	30-60	Over 60
Driveways per mile	-0.41	-0.03	+0.35
	Under 5%	5-10%	Over 10%
Intersections per mile	-0.99	+0.28	+1.55
	Under 5%	5-10%	Over 10%
Truck percentage	+0.40	-0.15	-0.71

Table 4. Accident severity distribution for suburban arterial highways.

Design Alternative	Percent of Accidents Involving a Fatality or Injury: Nonintersection Accidents, Commercial	Nonintersection Accidents, Residential	Unsignalized Intersection Accidents, Commercial	Unsignalized Intersection Accidents, Residential
2U	38.4	43.6	39.0	32.9
3T	29.9	43.6	32.1	32.9
4U	38.4	38.8	32.1	32.9
4D	33.7	43.6	26.9	45.1
5T	33.7	38.8	32.1	26.6

Table 5. Distribution of accident types susceptible to correction by multilane design alternatives.

Design Alternative	Percent of Accidents Susceptible to Correction[a]: Nonintersection Accidents, Commercial	Nonintersection Accidents, Residential	Unsignalized Intersection Accidents, Commercial	Unsignalized Intersection Accidents, Residential
2U	50.5	44.3	55.9	50.5
3T	45.0	49.4	65.2	56.7
4U	45.8	51.6	65.0	63.5
4D	58.6	43.2	55.3	42.4
5T	50.5	60.0	44.6	55.0

[a] Head-on, rear-end, and angle accidents.

Harwood collected no delay data, but used the simulation model TWLTL-SIM to estimate stops and delay on two-lane and four-lane suburban arterials both with and without TWLTLs. He used the same model to estimate the reduction in delay that results from installing a raised median on a four-lane undivided arterial. The results of the operational comparison between four-lane undivided and four-lane divided sections were compared with the effectiveness of five-lane TWLTL sections. Two major conclusions were drawn. First, at flow rates of 900 vph and below, median dividers generally result in an increase in delay. However, at flow rates of 1,100 vph and above, the installation of a median divider on an undivided street reduces delay, even for minimal levels of left-turn demand. These results suggest that the breakpoint where a median divider begins to provide operational benefits is a flow rate of approximately 1,000 vph in each direction of travel. Second, the 5-lane TWLTL design alternative is preferable to both the 4-lane undivided and the 4-lane divided design alternatives for all levels of flow rate, left-turn demand, and driveway density. "This result provides strong evidence that, strictly from an operational standpoint, the use of a TWLTL is a highly desirable alternative in a wide variety of design situations."

<u>Harwood</u>, Douglas W., and John C. Glennon, "Selection of Median Treatments for Existing Arterial Highways," Transportation Research Record 681, Transportation Research Board, Washington, 1978, pp 70-77.

This report looks at five different types of median treatments, the TWLTL, the continuous left-turn lane, the alternating left-turn lane, the raised median divider and the median barrier. Each alternative was analyzed to determine which one would reduce accidents and delay the most.

Regression equations were used to project the accidents on facilities with certain types of median, with each median type analyzed at three levels of ADT and development. Benefit-cost ratios were calculated using the delay and accident reduction data (benefits) and the cost of improving a road to have a certain median treatment (costs) for three different levels of construction.

Results were then tabulated based on these benefit-cost ratios. The final result was a table which allowed the user to determine the preferential median treatment by entering with the level of development and the ADT of the arterial. Caution is advised by the author, since the data used to arrive at the benefit-cost ratios involves construction costs at the time of writing and numbers of accidents based on regression equations, which do not always accurately reflect the actual relationship between the desired variables. Their table of benefit-cost ratios indicate that a TWLTL is preferred even for high ADT and high levels of roadside development. That is, there is no indication that a TWLTL ceases to enjoy its well-known benefits once a certain level of activity is reached.

<u>Harwood</u>, Douglas W., and C. J. Hoban, <u>Low-Cost Operational and Safety Improvements for Two-Lane Roads: Informational Guide</u>, Federal Highway Administration, Washington, D.C., 1986, pp 66-67.

This report is a review of existing literature. The authors review previous studies showing that the installation of a TWLTL on a 2-lane road reduces delay, particularly at higher-volume urban-fringe sites. Regarding accidents, the authors quote Harwood and Glennon, 1978, who reported that TWLTLs reduce accident rates by about 35 percent, when installed at urban and suburban sites, primarily on multilane highways. Comparable accident reduction effectiveness was found by Harwood and St. John (1986) for installation of TWLTLs on 2-lane highways in urban fringe areas. In rural areas the number of accidents at candidate TWLTLs on 2-lane highways is small, but TWLTLs can reduce these accidents by up to 85 percent.

<u>Harwood</u>, Douglas W., and A. D. St. John, <u>Passing Lanes and Other Operational Improvements on Two-Lane Highways,</u> FHWA/RD-85/028, Washington, D.C., 1985, pp. 99-100.

The authors developed a regression equation to predict the potential delay reduction from installing TWLTLs on 2-lane highways. There were only two data points at high volumes, so the model had little statistical significance.

Heikal, Aly S., and Zoltan Nemeth, "Measure of Potential Benefits from Two-Way Left-Turn Lanes, ITE Journal, June 1985, pp. 22-24.

The authors propose, and adopt for their research, a level-of-service concept by which the quality of mid-block traffic flow is measured by the friction created by mid-block left turns. The average number of stops per vehicle in the inside lane is taken as a measure of conflict between midblock left turns and through traffic. The authors applied this concept only to the inside lanes of four-lane arterials, and used the number of stops only to measure the potential for improvement in through-traffic flow by the installation of TWLTLs. However, the variable could just as well be used in studies of existing TWLTLs to determine the level of left-turning volume at which the TWLTL is no longer to function properly. The authors believe, based on professional judgment, that more than 0.3 stops per vehicle in the inside lane, over the length of a typical city block, indicates a definite need for improvement.

Highway Research Board, Highway Capacity Manual - Special Report 87, Washington, D.C., 1965.

The old Capacity Manual states that with respect to TWLTLs compared with divided sections "Logically, however, because lane capacity is reduced by side interference, among other things, and the raised median will eliminate the side interference on the left and reduce it on the right, the capacity of a divided roadway with protected left-turn lanes will exceed that of a five-lane facility."

Hoffman, M.R., "Two-Way Left-Turn Lanes Work!" in Traffic Engineering, August, 1974, pp. 24-27.

Studies of four Michigan arterials showed that, where no median was previously provided, the installation of continuous TWLTLs reduced total accidents by about 33 percent, with reductions of 45 and 62 percent for head-on and rear-end type accidents, respectively. Mr. Hoffman mentions the limitation of the TWLTL when left-turn volume reaches the capacity of the TWLTL. When this occurs, the facility breaks down and tends to operate more like a typical four lane highway. He goes on to mention that careful driveway planning (working to ensure that driveways, where possible, are positioned opposite other driveways) contributes to the successful operation of a road with a TWLTL. If driveways are positioned such that left-turning traffic interlocks, the efficiency of the facility drops very quickly. He also supports the planning and construction of "service drives" at large shopping centers which serve to channel the traffic to specific exit points in an effort to control access better.

Hurdle, V.F., and P.K. Datta, "Speeds and Flows on an Urban Freeway: Some Measurements and a Hypothesis," Transportation

Research Record 905, Washington, 1983, pp. 130-131.

This report was written to prove the hypothesis that the speed of an expressway may not depend on the flow rate as much as it depends on whether or not the flow is a capacity flow discharged from an upstream queue.

To prove this, the authors first determined the capacity of their subject freeway by performing 2-minute counts during the peak periods of three days, converting these to equivalent flow rates and then graphing the flow rates versus time.

These counts were done in the morning, between 6:30 and 9:00, under the assumption that capacity flow would be achieved somewhere during that interval. By observing the histograms, the authors determined that capacity flow was reached between 7:00 and 8:30. They then averaged the flow rates over this 1-1/2 hour period and found the average to be 1984 pcphpl. Although the authors felt this could be the capacity, they were of the opinion that the term "capacity" needed clarifying in terms of how long a time the capacity flow is maintained.

Institute of Transportation Engineers Committee 4A-2, Report on the Recommended State of the Art Practice for the Design and Use of the Two-Way Left Turn Lane, Institute of Transportation Engineers, Washington, 1978.

This report addresses two issues relevant to median design, especially TWLTLs: 1) the experience of state, county, and city traffic engineers with TWLTLs, and 2) general warrants for the use of TWLTLs.

The experience part of the report was summarized from the results of a survey sent to traffic engineers. The range of questions covered the type and length of experience engineers had with TWLTLs, how they were marked, what happened to the accident rate after installation, and what factors were used to determine if the installation of a TWLTL is warranted.

The warrant for a TWLTL, according to this report, is strictly based on ADT and type of use, although the report acknowledges that left turning volumes are also important when determining whether or not to install one.

Institute of Transportation Engineers Committee 5-5, Guidelines for Urban Major Street Design, Institute of transportation Engineers, Washington, 1979, pp. 7-1-8-10.

Section 7 of the Guidelines addresses median design, which "should be considered for all major urban streets of four or more lanes." Median types are discussed generally and the TWLTL is suggested as an alternative when high commercial development and inadequate right-of-way exists for wide medians with left-turn pockets.

Section 8 discusses TWLTLs and their applications in general terms. Because unrestricted access is so typical or major routes in urban and suburban areas, it should represent a basic design alternative. The general recommendations are that if faced with narrow right-of-way and high turning maneuvers and/or pressure from businesses desiring access to the highway, a TWLTL is the best alternative. If these problems do not exist, a wide median with left-turn pockets at intervals is preferred. The indirect left turn (like a jughandle) is also discussed and advocated as a possible solution. The section mentions that some way must be provided to serve both the through driver and the driver desiring to access abutting property, and that when parallel roads or service roads acting as frontage roads do not exist, a TWLTL is the best solution.

Also mentioned is the fact that there are two basic types of TWLTLs. One is differentiated by the fact that the TWLTL is carried through all intersections with no change in markings for the left-turn lane at major intersections. The other type involves terminating the TWLTL in order to provide a left-turn lane at major intersections.

<u>Institute</u> of Transportation Engineers Technical Committee 5B-4, "Effectiveness of Median Storage and Acceleration Lanes for Left-Turning Vehicles," <u>ITE Journal</u>, March, 1985, Washington, p. 61.

This article presents the results of a survey of Canadian and American municipalities concerning their experience with median treatments. Two major types of median treatments were considered: median acceleration lanes which separated traffic traveling to or from the minor street from the through lanes, and TWLTLs. The overall opinion was positive towards TWLTLs, with response to median acceleration lanes being mixed. No extensive use guidelines are given, and the paper mentions that "more research is needed to develop guidelines... [for]... the appropriate. . . median treatment for site specific roadway and traffic conditions."

General guidelines are given for TWLTL use. The article states that TWLTLs are best for strip development, should not be used for through traffic, and that TWLTLs must be signed and marked well to reduce indicision and misuse.

<u>JHK</u> & Associates, <u>Design of Urban Streets Student Textbook</u>, U.S. Department of Transportation, Washington, 1977, pp. 6-6.

The initial introduction to TWLTLs states that they are most commonly used on streets with dense adjacent development. It goes on to say that TWLTL operation has proven to be safe and that they result in less delay and disturbance to the overall traffic flow. In the portion of the textbook which discusses medians, TWLTLs are mentioned as a good method of access control, and the reader is referred to Nemeth's report for guidelines on the installation and use of TWLTLs. Mention is also made that care must be taken in TWLTL use, since high turning volumes in TWLTLs can contribute to increased accident rates.

Knoblauch, R. L., M. R. Parker, Jr., and J. C. Keegel, Traffic Control for Reversible Flow Two-Way Left-Turn Lanes, Final Report, FHWA-RD-85/009, Federal Highway Administration, Washington, D.C., October, 1984.

The authors suggest replacing the flashing yellow "X" with the flashing doube-yellow arrow symbol.

Lebel, William T., letter to Mark R. Norman of May 10, 1985 and attached in-house report, State of Michigan Department of Transportation, Lansing, Michigan.

Michigan generally uses TWLTLs in situations (2, 4, or 6 through lanes) with high levels of strip development. Lebel recognizes that the effectiveness of TWLTLs is limited at high volumes, since left turns into and out of abutting businesses become difficult. Lebel also mentions that pedestrian crossing placement is limited due to the lack of signal placement flexibility, and that future highway expansion (like to a divided section) is not practical once abutting development is in place because of right-of-way constraints.

Lebel goes on to mention that a five-lane section near Grand Rapids, which has an ADT of 40,000 is not "operat[ing] as favorable as it does at lower levels. In this case there is little doubt in our mind that a boulevard-type design is preferred." He states that a boulevard-type design (through traffic lanes separated by a grassed median with left-turn pockets at major intersections and at intervals between intersections) would allow left turns to be made at these designated crossovers (later referred to as directional median crossovers), where signalization could be provided to control the left turn movements without compromising through capacity. He cites Savage's article in the August, 1974 issue of Traffic Engineering for further descriptions of the directional median crossover concept.

For a situation with ADT in the upper 40,000's and wide right-of-way, he recommends a six-lane section with planned U-turns at signalized intersections.

An attached report mentions that "at capacity, left turn movements become very difficult either onto or off from the facility." It mentions that boulevard-style design is preferred when building a new arterial or widening an existing arterial in an undeveloped area. The report also states that accidents related to left-turning vehicles have been found to decrease when TWLTL's are installed on a facility previously having no provision for mid-block left turns.

Levenson, Herbert S., et. al., "Callahan Tunnel Capacity Management," Transportation Research Record 1005, Washington, 1985, pp. 4-5.

This report addresses the need to equalize the capacity of a tunnel at all points along the tunnel. Prior to the implementation of the measures designed to equalize flow, a capacity analysis of the tunnel was performed. The capacity was determined by looking at other similar tunnels for which maximum observed volumes were known. These volumes were averaged and compared with the capacity as calculated in the Highway Capacity Manual to estimate the capacity of the tunnel.

McCormick, David P., and Eugene M. Wilson, "Comparing Operational Effects of Continuous Two-Way Left Turn Lanes," University of Wyoming, Laramie, no date, pp. 6-7.

This report compares TWLTLs with two other median treatments: no median treatment, and the alternating left-turn lane. They determined effectiveness by a conflict analysis and found the TWLTL to reduce conflicts considerably over either of the two other treatments. The only volume requirements mentioned were ADTs of 10,000 to 20,000. The assumption here is that the number of conflicts are directly proportional to the number of accidents on a highway. Although volumes of the study roadways are given, no mention is made of the effectiveness of any of the median treatments at high or low volumes.

McCoy, Patrick T., et. al., "Operational Effects of Two-Way Left-Turn Lanes on Two-Way Two-Lane Streets," Transportation Research Record 869, Transportation Research Board, Washington, 1982, p. 53.

This report evaluated operational effects of a TWLTL from a computer simulation viewpoint. McCoy used the General Purpose Simulation System (GPSS) language to simulate the operation of a two-lane road with a TWLTL. Different traffic volumes and different driveway densities were used and their effectiveness was measured in terms of reductions of number of stops and reduction of delay.

McCoy, Patrick T., Guidelines for the Use of Two-Way Left-Turn Lanes, Federal Highway Administration, Washington, D.C., 1986, preliminary report.

This is a follow-up simulation study to the one cited above. TWLTL-SIM was written to simulate a 5-lane section with TWLTL. Using Gerlough and Wagner's gap-acceptance function, he determined the probability (of a driver's accepting a certain gap) to determine the needed gap for making a left turn. Unfortunately, the model is designed to abort left turns when those turns cause a jammed flow situation.

McDonald, J.W., "Relation Between Number of Accidents and Traffic Volume at Divided Highway Intersections," Highway Research Bulletin 74, Highway Research Board, Washington, 1953.

This report presents a prediction equation for the expected accident experience of four-way, unsignalized intersections on divided highways.

Mulinazzi, T.H., and H.L. Michael, "Correlation of Design Characteristics and Operational Controls With Accident Rates on Urban Arterials," Joint Highway Research Project, Purdue University and Indiana State Highway Commission, 1967.

This report presents regression equations for accident rates on urban arterials and is used as the basis of the regression data in Glennon's work.

Nemeth, Zoltan A., "Development of Guidelines for the Application of Continuous Two-Way Left-Turn Median Lanes," The Ohio State University, July 1976, pp. 6-9.

This report began with a literature review in order to determine the conditions under which TWLTLs were implimented and how the TWLTLs impacted the quality of flow along the arterial. The traffic volume section mentions several capacity-oriented figures. The range of volumes which were served by a TWLTL were from 8,000 to 31,000 ADT, and it was mentioned that accident reductions were seen at all ranges of volumes.

The Georgia Division of the ITE concluded, from their literature search, that TWLTLs are best used on five-lane facilities with volumes between 10,000 and 25,000 ADT. Below 10,000, three-lane facilities can be used successfully. The Georgia ITE report also mentioned "that as traffic volumes approach capacity, the gaps in opposing traffic available for left turns are very limited, so that the value of the TWLTL in reducing congestion then becomes questionable."

Sawhill and Hall of the University of Washington also stated that "Traffic volumes as such are not always found to be a warrant, but volumes approaching roadway capacities in either direction may be a reason for not installing the TWLTL; more important would be the observation of time gaps of sufficient length for left turn movements to be accomplished." The Washington State Department of Highways uses TWLTLs only on facilities with ADTs between 10,000 and 25,000 for multilane facilities and between 5,000 and 12,500 for two-lane facilities. The report mentions that more investigation might be justified on the effect of the TWLTL at the limits of the ADT range before conclusive results can be stated.

The report presents the results of three before-and-after studies done on Ohio arterials. In two out of the three situations, traffic flow conditions improved in the after case, with the one degredation occuring when a road used as a four-lane highway was re-striped as a three-lane highway. Nemeth measured the effectiveness of the TWLTL in terms of average running speed and average running time over the modified section, and in number of brakings and weavings on the highways. He felt that TWLTLs were a success in terms of increasing overall speed and reducing brakings and weavings (which he felt were an indication of too many conflicts).

<u>Nemeth</u>, Zoltan A., "Impact of Two-Way Left Turn Lanes on Fuel Consumption," Transportation Research Record 901, Transportation Research Board, Washington, 1983, p. 32.

This report analyzes the benefits derived from TWLTLs and expresses those benefits in terms of annual reduction in fuel consumption, dependant on driveway density, ADT, and left turn volume. The reduction is compared to the "do-nothing" alternative, and shows significant consumption reductions with two-lane sections, and small, sometimes significant consumption reductions with four-lane sections.

<u>Nemeth</u>, Zoltan A., <u>Two-Way Left-Turn Lanes: A State-of-the-Art Overview and an Implementation Guide</u>, Ohio State University, 1978 pp 13-17, also in Transportation Research Record 681, Transportation Research Board, Washington, 1978, pp. 62-69.

This material analyzed the effectiveness of TWLTLs on the basis of average running speeds and number of "erratic maneuvers" (weavings and brakings) when compared to the "before" condition, which was always no form of median. In conditions where the TWLTL was added with no loss of existing through lanes, the TWLTL was found to decrease the number of erratic maneuvers and usually increased the overall running speeds.

<u>Newman</u>, Earl E., letter to James A. Thompson of February 27, 1979, city of Springfield, Missouri traffic engineer.

According to Mr. Newman's letter, a five-lane section (four through lanes plus a TWLTL) is a traffic engineering tool to be used on existing facilities in order to maximize capacity. He does not recommend it for an initial design of a roadway through relatively undeveloped areas. In that case, he prefers a section involving some sort of median with left turn pockets at intervals. He gives accident and traffic volume data for three different highways in support of his recommendations. Two are five-lane sections with ADTs of 20,000 and 37,000, and the third is a four-lane divided highway with 14,000 ADT. The accident data shows a lower accident rate on the four-lane divided section, with the major difference in accidents showing up in a comparison of mid-block accidents over a 12-month period. The divided section had one-third the accidents of the lower of the two undivided sections over the same time period. Other information gives the capacity of an expressway as 750 vphpl.

Parker, Martin R., Jr., "Guidelines for Selecting Median Treatments for Urgan Highways," Compendium of Technical Papers - Institute of Transportation Engineers 49th Annual Meeting Toronto, Canada, Washington, 1979, p. 77.

This paper was written to present a series of regression equations which were to provide the highway engineer with information concerning the preferred type of median treatment on a certain facility. These equations took into account the ADT, streets and signals per mile, local population and driveways per mile. For each type of median treatment, two equations were developed, one for accident estimate and the other for delay estimates on the facility.

Parker's data was gathered from a sampling of roads in the northern Virginia area with examples of raised, traversable and undivided sections comprising the sample.

Parker, M. R., Jr. and K. H. Tsuchiyama, Traffic Control for Reversible Flow, Two-Way Left-Turn Lanes, State-of-the-Art Report, FHWA-RD-85/010, Federal Highway Administration, Washington, D.C., October, 1984.

The authors present traffic control and effectiveness information for 19 sites with reversible-flow, TWLTL operations.

Parker, Martin R., letter to Mark R. Norman of May 22, 1985, Engineering Consultant, Canton, Michigan.

This letter is addressing seven-lane sections (six through lanes with a TWLTL) and determines that from past data collection, seven- and five-lane sections have similar accident rates. The seven-lane sections mentioned had ADTs in the upper 20,000 range.

Rosenbaum, Merton, "Traffic Control for Reversible Flow Two-Way Left-Turn Lanes", Public Roads, Washington, D.C., June, 1986, pp. 1-10.

The article focuses on driver understanding of signage for this unusual arrangement of lanes. Research results resulted in the proposal of *MUTCD* amendments in 1985 to allow a static sign system as an alternate to lane-use control signals, certain new

pavement markings, and a new, non-flashing TWLTL signal.

<u>Royer</u>, David C., letter to Mark R. Norman of May 15, 1985, Principal Transportation Engineer, City of Los Angeles.

Mr. Royer is defending the Los Angeles policy of using TWLTLs whenever possible. The advantages he cite include: reducing travel distance, improved intersection efficiency, reduces left-turn phasing requirements, improves operation of emergency vehicles, reduces maintenance costs, construction traffic routine, eliminates the median as a fixed object, allows for striping revision at minimal cost, and acceptance of the TWLTL by the business community. He also cites the fact that total accident rates have not increased with TWLTL installation.

<u>Savage</u>, William F., "Directional Median Crossovers," <u>Traffic Engineering</u>, August, 1974, Washington, pp. 21-23.

This article explains the concept of indirect left turns at intersections of major roads in Michigan. In an effort to reduce congestion and delay at major intersections, indirect left turns are accomplished by having the motorist turn right onto the major highway and then make a U-turn through a directional crossover to travel in the desired direction. He explains that this concept is used with highways having very wide medians to accomodate the crossover (U-turn) lane, and that it does reduce delay and congestion. Since phasing is reduced at the intersection (no left-turn phasing is necessary), the capacity of the intersection is increased and traffic flows more smoothly.

<u>Sawhill</u>, Roy B., and Jerome W. Hall, "Investigation of Left-Turn Movements on Arterial Streets and Highways", <u>Traffic and Operations Series, Research Report No. 13</u>, Transportation Research Group, University of Washington, November, 1968.

The authors stated that "traffic volumes as such are not always found to be a warrant, but volumes approaching roadway capacities in either direction may be a reason for not installing the TWLTL, more important would be the observations of time gaps of sufficient length for left-turn movements to be accomplished".

<u>Sawhill</u>, Roy B., and Dennis R. Neuzil, "Accidents and Operational Characteristics on Arterial Streets with Two-Way Median Left-Turn Lanes," Highway Research Record 31, Highway Research Board, Washington, 1962, p. 54.

This report, concerning the first TWLTL installation in the country, does address the volumes using a TWLTL. According to their volume counts, the peak hour volume was 232 TWLTL movements/hour. In addition, the overall TWLTL volume was found to be approximately 23% of the total volume counted (over a 12-hour period). The peak hour was the noon hour. The report also shows graphs of the TWLTL volume over the count period. Head-on collisions on TWLTLs were shown to be an uncommon occurrence and of negligible concern.

Shaw, R. B., and H. L. Michael, "Evaluation of Delays and Accidents at Intersections to Warrant Construction of a Median Lane," Highway Research Record 257, Highway Research Board, Washington, 1968, pp. 17-33.

This report presents the results of a study involving the need for left-turn lanes at high-volume intersections. The two determining criteria for the left-turn lane were delay and accident data. The authors determined the cost of the delay and the average cost of an accident, and compared the benefit gained by the installation of a left-turn lane to the cost of the construction and maintenance of that left-turn lane. If the benefit was greater than the cost, it was determined that the lane was worth constructing.

SOAP 84 User's Manual, U.S. Department of Transportation, Washington, 1985, pp. B-19-B-21.

The SOAP 84 user's manual presents a model for the determination of the capacity of an unprotected left turn interval, which could be used for the calculation of the capacity of a TWLTL or other median treatment. The model used for this calculation was taken from the NETSIM model and relates opposing flow and minimum headways necessary for left turn movements.

Stover, Vergil G., et al., "Guidelines for Medial and Marginal Access Control on Major Roadways," National Cooperative Highway Research Program Report 93, Highway Research Board, Washington, 1970, pp. 32-45.

This report advocates left turns from major arterials at intersections only, unless there is adequate median width to provide left turn pockets at specific mid-block locations. TWLTL's are not discussed as an alternative. This report is advocating restricted access as much as possible, allowing any sort of access only if a median of sufficient width is provided for cars to decelerate before a left turn or accelerate after a left turn onto the arterial.

Stover, V. G., et. al., "Chapter 4 -- Access Control and Driveways," in Synthesis of Safety Research Related to Traffic Control and Roadway Elements, Vol. 1, Report No. FHWA-TS-82-232, Federal Highway Administration, December, 1982.

This literature review reports the results of Horne and Walton, Sawhill and Neuzil, Nemeth, and Glennon, et. al. Those results are shown in this annotated bibliography under the respective authors.

Thakkar, Janak S., "A Study of the Effect of Two-Way Left-Turn Lanes on Traffic Accidents, Illinois Department of Transportation, Springfield, 1983.

This report presents the results of a study of highways with TWLTLs and the effect the TWLTLs had on accident rates at high accident locations. In all cases, rates had fallen and the severity of accidents was reduced, also. A benefit-cost analysis was performed and concluded that TWLTLs were an economic and safe alternative on highways with very high levels of roadside development.

Thompson, James A., letter to Tom Brahms of June 26, 1984, transmitting notes of TWLTL Counterpoint meeting held in Chicago.

This meeting stated that TWLTLs were appropriate on minor arterials with low, but mid-block left-turning demands and in situations where no other alternatives were practible. The meeting concluded that TWLTLs were not acceptable for reconstruction of arterial streets, that the need to control conflict points is too great on major arterials.

The meeting also recognized that access to businesses is a problem with raised medians. Consequently, the meeting saw the need to coordinate with businesses the construction of common driveways at access points. At non-developed areas, the conclusion was that the engineer was losing an opportunity to influence future development and access.

Thompson, James A., letter to Mark Norman of May 16, 1985, transmitting TWLTL information gathered during research, city of Des Moines, Iowa.

Mr. Thompson feels that the upper limit for a five-lane section is 25,000 ADT and that 40,000 is too much for a seven-lane section. He uses these limits as the result of research he did for Des Moines which determined the median treatment for an urban arterial, given accident rates, mid-block left turn volumes, and street traffic volumes.

In a report he wrote which was included with his letter he mentions that the accident rate for a four-lane divided arterial is significantly lower than that of a five-lane facility, and that "the midblock accidents on a TWLTL carrying 37,000 vehicles per day are alarming." Also, "If the future land use goals of a community include containment of strip-type commercial development, then the TWLTL is not the best choice."

Transportation Research Board, Highway Capacity Manual - Special Report 209, Washington, 1985, p. 7-3, 11-2.

The new Capacity Manual requires that multilane roads be divided into one of four major types with the following major characteristics: urban or suburban, divided or undivided. The Manual recognizes that there are many different types of median treatments which might categorize a road as somewhere inbetween divided and undivided. It also recognizes that there are several different types of median treatments which involve some sort of continuous left turn lane. The Manual, in general terms, compares the relative capacity of a facility with some sort of median treatment to a similar road without any form of treatment, concluding that a road with a median treatment intended to provide better left turning conditions will have less friction than one without any treatment.

The Manual also states that the determination of a road as rural or suburban depends on several factors, like the frequency of unsignalized intersections, driveways and other uncontrolled access points, and the number of left and right turns into and out of these access points.

The determination of a multilane road as urban or suburban, divided or undivided allows the determination of an "Adjustment Factor for Type of Multilane Highway and Development Environment." The Manual realizes that this method does not recognize various types of median controls explicitly, but advises the user to interpolate between the tabulated values of the Adjustment Factor to compensate for the different types of median treatments.

Chapter 11, Urban and Suburban Arterials, discusses the methodology of determining the level of service of an arterial, but does not discuss the capacity of an arterial, stating that "the capacity of an arterial is generally dominated by the capacity of its signalized intersections. . . . In some cases, there are special midblock restrictions that also limit the capacity." The user is then referred to Chapter 9, Signalized Intersections, for determining the capacity of a signalized intersection.

The new capacity manual, addressing the capacity of unsignalized intersections states that the capacity of an unsignalized intersection is determined by first determining the ideal capacity of the movement, and then factoring that capacity down due to the effects of conflicting movements on the desired movement. Graphs are used to determine both the ideal capacity and the factors for adjustment. These graphs use critical gap length and opposing flow rate and the capacity used by the existing demand to determine the capacity of a movement.

Voorhees, Alan M., and Associates, Quality of Flow in Urban Arterials - Phase I, Federal Highway Administration, Washington, 1978, pp. 19-31.

This report addresses the issue of arterial capacity, and recognizes that the limiting point of arterial capacity may not be at a signalized intersection. Its proposed method of analysis accounts for this.

The general method involves collecting geometric information about a length of arterial as well as volume information and running the NETSIM program using this data. The data collection is complex and tedious, but careful data collection would produce realistic results from the computer simulation. Since the program develops its model based on information gathered in the field, it could be run with data intended to make a section of arterial run at capacity, and could then determine the capacity of the section and therefore determine the capacity of the turning lane or other median treatment.

Walton, C. Michael, et. al., "Accident and Operational Guidelines for Continuous Two-Way Left-Turn Median Lanes," Transportation Research Bulletin 737, Transportation Research Board, Washington, 1979, pp. 43-53.

This paper looked at median treatments based on ADT, level of development, left-turn accidents and total accidents. Tabulated warrants for access control techniques were presented using the parameters just mentioned. It was concluded that TWLTLs produced lower accident rates at intersections, but that one-way left-turn lanes have lower accident rates at mid-block, driveway locations.

Washington State Department of Highways, "Two-Way Left-Turn Lanes", Policy Directive No. 24-15 (HT), Seattle, Washington, September 13, 1973.

The State of Washington uses TWLTLs on multilane roads with ADT between 10,000 and 25,000 and on two-lane roads between 5,000 and 12,500. Their upper limit of 25,000 ADT was echoed by Thompson (1985)

Welsh, Thomas M., "A Report on Median Treatments Utilized for the Improvement of Urban Arterial Streets," Iowa State University, Ames, Iowa, 1980, p. 23.

This paper recommends that arterials with traffic in excess of 15,000 ADT should have a raised median divider with left-turn bays, preferably, with the TWLTL as a second choice. The paper also quotes heavily from Glennon and Harwood's work in terms of choosing appropriate median treatments.

City of Wichita, Kansas, "Economic Factors Affecting Commercial Properties Adjacent to Raised Medians," Traffic Engineering Division, June, 1971, p. 8.

This report measured economic impact on businesses abutting a facility which had recently installed a raised median. Overall results showed an increase in revenue for businesses along the facility and a general increase in property values along the facility after the raised median was installed.

Appendix D

Field Data-Collection Forms

Data Collection Procedure

Several different types of data are to be collected at each collection site. These are: Volume, Travel Time , Roadside Development, Driveway Activities, Length of Study Area, Alignment, Lane Width, Median Width, Left Turning Bay Width and Length, and any valuable information pertaining to a particular site.

Two types of volumes will be collected: Through volumes and left-turning volumes. One person will count the through and the left-turning vehicles in one direction, using a hand tally, and the other counts the other direction in the same fashion. However, left turning vehicles will be counted in two different ways depending on the type of median. At a gap in the median, only vehicles that start at the arterial and make a left turn through that gap will be counted. In a TWLTL location, all left turning vehicles in a length of approximately 1000 feet will be recorded. (See form No.1)

Travel Time will be obtained using Georgia Tech's Van as a floating vehicle. It will be recorded in seconds using a stop watch.

The rest of the data collection will either be a direct measure using a Rolatape (driveway width, lane width, median width, etc.) or a simple observation such as roadside development (see forms 3 and 4).

Field Studies

Three different types of studies will be performed at each individual site. A delay study for Left-Turning vehicles only using the Epson Hx-20 lap top computer running the QUEDEL program.

A vehicle classification study to determine the different types of vehicle that use the study area, such as passenger cars, single unit trucks, etc. Using form No. 5, one person will count the total number of vehicles without regard of type, while another person will count the total number of CD (cars and pick-ups towing light recreational trailers), SU (single unit), 2-S2 (two axle semi-trailer) and 3S-2 (three axle semi-trailer). These counts will be done for 5 minutes in each direction).

Finally, the adequate gap study will be performed using a metronome, set at 60 beats per minute. We will look at only one direction of traffic to determine the duration of clear gaps between successive vehicles. This study will be done at the same time as the delay study.

Field Data Form
for
Median Treatment/TWLTL Project

Form No. 1

Date:__________ Observers:______________________ Weather______

Location: ____

County:______________ Start Time:_________ End Time: ________

Traffic Conditions (a.m., p.m., off peak): _________________

No. of through lanes (both directions):____________________

Road direction___________ Type of median treatment _________

Left-Turn and Through Volume Count

a) One person counts the through and the left-turning vehicles in one direction, using a hand tally, and the other counts the other direction in the same fasion. Count for 5 minutes. If you count less than 5 left-turning vehicles total, extend the count to 15 minutes.

Total Volume Count Duration:_________minutes

Direction:_______bound Direction:________bound

Total:___________ Total:____________

Equiv. hourly flow rate______ Equiv. hourly flow rate______

(Multiply by 12 if a 5 minute count, by 4 if a 15 minute count)

Flow rate, sum of both directions:_________________________

Avg. flow rate per lane:_______________ Split:_____________

b) If counting at a gap in a median, count vehilces that start on the arterial and make left turn through that gap. Also, make note of how many of those vehicles actually make a U-turn instead of just a 90 degree left turn.

If you're at a TWLTL location, pick a length of left turn lane and count every vehicle that uses that length of TWLTL.

Total:_________________ Number of U-turns observed:________

Equiv. flow rate:_______ % of total rate as left turns:____

Tape QUEDEL results here

Adequate Gap Study

Form No. 2

Location: ____________________ From ______________________________

to ________________________________ Date: _______________________

This study will be done in the same way that the crosswalk study was done. A metronome, set at 60, will be your timer. Look at only one direction of traffic, and determine the duration of clear gaps, that is, the amount of time between successive vehicles. Time about 100 gaps.

Gap Length (seconds)	Total length	Number of Gaps Av gap____ Std dev_____	Turns made in gap
1		1 ________________	1 ________
2		2 ________________	2 ________
3		3 ________________	3 ________
4		4 ________________	4 ________
5		5 ________________	5 ________
6		6 ________________	6 ________
7		7 ________________	7 ________
8		8 ________________	8 ________
9		9 ________________	9 ________
10		10________________	10________
11		11________________	11________
12		12________________	12________
13		13________________	13________
14		14________________	14________
15		15________________	15________
16		16________________	16________
17		17________________	17________
18		18________________	18________
19		19________________	19________
20		20________________	20________

Total: __________

Adequate Gap Study

Form No. 2b

Location: ____________________ From ______________________________

to ________________________________ Date: ______________________

This study will be done in the same way that the crosswalk study was done. A metronome, set at 60, will be your timer. Look at only one direction of traffic, and determine the duration of clear gaps, that is, the amount of time between successive vehicles. Time about 100 gaps.

Gap Length (seconds)	Total length	Number of Gaps Av gap____ Std dev_____	Turns made in gap
21		21 ________	21 ________
22		22 ________	22 ________
23		23 ________	23 ________
24		24 ________	24 ________
25		25 ________	25 ________
26		26 ________	26 ________
27		27 ________	27 ________
28		28 ________	28 ________
29		29 ________	29 ________
30		30 ________	30 ________
31		31 ________	31 ________
32		32 ________	32 ________
33		33 ________	33 ________
34		34 ________	34 ________
35		35 ________	35 ________
36		36 ________	36 ________
37		37 ________	37 ________
38		38 ________	38 ________
39		39 ________	39 ________
40		40 ________	40 ________

Total: __________

Field Data Form

Form No. 3

Date: __________ Location: ______________________________________

from __________________________ to ______________________________

Direction: _____ Bound Travel Time: _______ Distance: _____

No of Driveways: ______ Total Length of Driveways: ________

Comments: ____

____

____

Intersection Spacing: ___________ Alignment: ______________

No of Lanes: ______ Lane Width: _________ Speed Limit: _____

Shoulders: __________________ Median Width: _______________

Type of Traffic: ____

Roadside Development: ______________________________________

____

____

____

____

____

____

Driveway Activities: _______________________________________

____

____

____

____

<u>For Raised Medians:</u>

Left Turn Bay Length: ________ Left Turn Bay Width: _______

Type of Control Devices: ___________________________________

Total Driveway Length

Form No. 4

Location ______________________________

Direction: Travelling _______Bound; Driveways _____(N, S, E, W)

of ______________________ (Street) Date: ______________

1. ____________ feet to ______________________
2. ____________ feet to ______________________
3. ____________ feet to ______________________
4. ____________ feet to ______________________
5. ____________ feet to ______________________
6. ____________ feet to ______________________
7. ____________ feet to ______________________
8. ____________ feet to ______________________
9. ____________ feet to ______________________
10. ____________ feet to ______________________
11. ____________ feet to ______________________
12. ____________ feet to ______________________
13. ____________ feet to ______________________
14. ____________ feet to ______________________
15. ____________ feet to ______________________
16. ____________ feet to ______________________
17. ____________ feet to ______________________
18. ____________ feet to ______________________
19. ____________ feet to ______________________
20. ____________ feet to ______________________

VEHICLE CLASSIFICATION COUNTS

Form No. 5

Date: ____________ Location: ______________________________

from _________________________ to ______________________________

Day: _________________ Observer: __________________________

In the spaces under ___ Bound enter the types of vehicles you are counting; P, CD, SU, 2-S2, 3-S2.
Note: Cars and pick-ups towing light recreational trailers should be classified as CD, while those towing large heavy trailers are SU.

Begin Time   End Time   _____ B o u n d

__________ __________

Total ____Bound______

Subtotal=

Begin Time   End Time   _____ B o u n d

__________ __________

Total ___Bound_______

Subtotal=

Conclusions: ____

Appendix E

Description of Sites

No.	Location	Type
1T	SR 124 in Lawrenceville	TWLTL
2T	SR 20 in Lawrenceville	TWLTL
3T	Memorial Drive (east of Hairston)	TWLTL
4T	US 78 in Snellville	TWLTL
5T	Candler Road	TWLTL
6T	Cobb Parkway	TWLTL
7T	Old National Highway	TWLTL
8T	Roswell Road (inside the perimeter)	TWLTL
9T	GA-85	TWLTL
10T	Jonesboro Road	TWLTL
11T	Memorial Drive (at Dekalb College)	TWLTL
12T	Roswell Road (outside Perimeter)	TWLTL
13T	Memorial Drive (near I-285)	TWLTL
14T	Buford Highway (north of I-285)	TWLTL
15T	Buford Highway (south of I-285)	TWLTL
16T	Cobb Parkway (near Windy Hill Rd.)	TWLTL
1R	Moreland Avenue	R.M.
2R	Forest Parkway	R.M.
3R	Buford Highway	R.M.
4R	Tara Boulevard	R.M.
5R	GA-85	R.M.
6R	Holcomb Bridge Road	R.M.
7R	Fulton Industrial Boulevard	R.M.

Site Description

For the purpose of this study, a total of 23 sites were selected, 16 Two Way Left Turn Lane (TWLTL) and 7 of the Raised Median type. These sites are further classified in terms of driveways per mile and their Annual Average Daily Traffic (AADT). They are separated as follows:

Low Driveways per mile = Less than 50

Medium Driveways per mile = Between 50 and 100

High Driveways per mile = More than 100

and

Low AADT = Less than 18,000

Medium AADT = Between 18,000 and 30,000

High AADT = More than 30,000

Table 3.1 lists all sites.

<u>S.R. 124 in Lawrenceville:</u>

This site is located inside the city of Lawrenceville extending from Gwinnett Drive to a point 0.2 miles north. It is a TWLTL with an AADT of 17,960 and 75 Driveways per mile. It is mainly lined with a gas station, one restaurant, a Gwinnett County building, one private residence, a decorating store, a furniture store and a large shopping center.

The cross section consists of two 12 feet through lanes (one for each direction) and a 13 feet TWLTL. There is a side-walk on the west side only and no lights are provided on either edge.

The traffic is composed of about 97% passenger cars and 3% trucks and recreational vehicles.

S.R. 20 in Lawrenceville:

This site is located inside the city of Lawrenceville extending from Phillips Street to Applewood Drive, a total of 0.18 miles. The direction of this TWLTL section is East-West and has an AADT of 15,487 and 85 Driveways per mile. To the sides of this roadway you find a shopping center, a Mrs. Winners fast food, 2 private residence, a U-Haul rental store, a Goodyear tire shop and the St. Lawrence Rectory.

The cross section consists of two 12 feet through lanes (one for each direction) and a 13 feet TWLTL. There is a curb on one side of the street, but no sidewalks are provided. Street lights are found on the north side of the section approximately every 300 feet.

The traffic is composed of about 95% passenger cars and 5% trucks and recreational vehicles.

Memorial Drive (east of Hairston):

This is one of the two sites located in State Route 10 near the vicinity of Stone Mountain. It is a TWLTL with an AADT of 28,300 and 35 Driveways per mile. The section extends from Englewood Drive to a point 0.2 miles east. To

the sides of the road you find 2 private residence, an apartment complex, a motel and a sporting goods shop.
The cross section consists of six 12 feet through lanes and a 13 feet 6 inches TWLTL. No sidewalks nor lights are provided at this site.
The traffic is composed of about 98% passenger cars and 2% trucks and recreational vehicles.

U.S. 78 in Snellville:

This site is located just outside the city limits of Snellville. It extends from Cindy Lane to a point 0.2 miles east. It is a TWLTL section with an AADT of 22,380 and 60 Driveways per mile. To the sides of the road you find a restaurant, Ken's pizza, a used car place, a private residence, a tax service building and a nursery school.
The cross section consists of four 12 feet through lanes and a 12 feet TWLTL. There is a sidewalk on the north side of the section and lights are provided on one side only.
The traffic is composed of about 98% passenger cars and 2% trucks and recreational vehicles.

Candler Road:

This site is located near the vicinity of Atlanta. It is a TWLTL and extends from Eastwyck Road to Misty Waters Drive. It has an AADT of 21,530 and 105 Driveways per mile. To the sides of the roadway you will find a liquor store, 4 fast food places, a car wash, a tune up clinic, am empty building and a gas station.

The cross section of this site is composed of four 10 feet through lanes and a 12 feet TWLTL. There are sidewalks on both sides of the road.

The traffic is composed of about 97% passenger cars and 3% trucks and recreational vehicles.

Cobb Parkway:

This site is located in Smyrna which is a suburban area near the vicinity of the city of Marietta. It extends from Spring Road/Circle 75 Parkway to a point 0.2 miles north. It is a TWLTL with an AADT of 45,566 and 65 Driveways per mile. It is mainly lined with 7 fast food places, a Dunkin Donuts, an office building and Service Merchandise.

The cross section consists of four 12 feet through lanes and a 15 feet TWLTL. Both sides have curbs on their sides but no sidewalks are provided.

The traffic is composed of about 97% passenger cars and 3% trucks and recreational vehicles.

Old National Highway:

This site is located in south Fulton County. It extends from Old Bill Cook Road to Jolly Road which adds up to a total of 0.19 miles. It is a TWLTL with an AADT of 45,360 and 80 Driveways per mile. To the sides of this road you find 9 fast food places, some of which share the same driveway, a car wash, an empty lot, 2 banks and wholesale mattress house.

The cross section is composed of four 12 feet through lanes and a 12 feet TWLTL. There is a sidewalk on the west side and no light are provided on either side.

The traffic is composed of about 99% passenger cars and 1% trucks and recreational vehicles.

Roswell Road (inside the perimeter):

This site is located inside the city of Atlanta extending from Rickenbacker Drive to Midvale Drive, or a total of 0.19 miles. It is a TWLTL with an AADT of 32,745 and 65 Driveways per mile. It is mainly lined with a shopping mall, a residence, a fruit stand, a paint shop, an auto sound shop, 2 sets of apartment complex and 2 condominiums. The cross section consists of four through lanes, 11 feet outside lanes and 10 feet inside lanes, and a 10 feet TWLTL. There are sidewalks on both sides of the road. The traffic is composed of about 98% passenger cars and 2% trucks and recreational vehicles.

GA-85 (north end):

This is one of the two sites located in S.R. 85 inside the limits of the city of Riverdale. The section extends from Valley Hill Road to a point 0.2 miles south. This TWLTL has an AADT of 36,233 and 140 Driveways per mile. To its sides you find 11 fast food places, a package store, a gas station, an office building, a library, a parking lot and a health food place.

The cross section consists of six 12 feet through lanes, except the outside lanes which are 11 feet wide, and a 12 feet TWLTL. There are sidewalks on both sides of the road as well as street lights approximately every 300 feet.

The traffic is composed of about 97% passenger cars and 3% trucks and recreational vehicles.

Jonesboro Road:

This site is located near Forest Park in Clayton County. It extends from College Street/Thurmond Road to a point 0.2 miles south. This site has an AADT of 32636 and 100 Driveways per mile. It is mainly lined with 3 fast food places, a parking lot, a church, a shopping center, an auto sales place, a body shop and a copy place.

Its cross section consists of four 12 feet through lanes and a 13 feet TWLTL. Both sides have a curb but no sidewalks are provided.

The traffic is composed of about 97% passenger cars and 3% trucks and recreational vehicles.

Memorial Drive (at Dekalb College):

This site is located about one mile outside the perimeter in S.R. 10 extending from the Dekalb College entrance to a point 0.27 miles east. It is a TWLTL with an AADT of 43,395 and 107 Driveways per mile. To the sides of this road you find 7 fast food places, a U-Haul rental place, an auto shop, a CMC stereo store, a rent a car place, an empty building, a plaza and a Color Tile/Pro Golf store.

The cross section consists of six 12 feet through lanes and a 12 feet TWLTL. Both sides have a curb but no sidewalks are provided.

The traffic is composed of about 97% passenger cars and 3% trucks and recreational vehicles.

Roswell Road (outside the perimeter):

This is one of the pilot sections located in the Atlanta suburb of Sandy Springs, extending from Sandy Springs Place to Hilderbrand Drive, or 0.18 miles. It is a TWLTL with an AADT of 35,730 and 115 Driveways per mile. This stretch of road has six restaurants, two office buildings, a used car lot, a boat sales lot, a muffler shop, a pair of real estate offices, two small strip shopping centers and one medium-size shopping center.

The cross section of this site is composed of four 10.5 feet through lanes and a 10 feet TWLTL. Sidewalks are provided on both sides of the road.

Traffic on Roswell Road is predominantly passenger cars and light trucks, with approximately 10% of the total traffic made up of single unit (SU) trucks and buses. Very few tractor-trailer (WB) trucks were observed.

Memorial Drive (near I-285):

This site extends from 0.2 miles east of I-285 to a point 0.2 miles east. It is a TWLTL with an AADT of 55,400 and 55 driveways per mile. To the sides of the road you find two gas stations, a Denny's, Steak'n Shake, Church's Fried Chicken, Wendy's, and a Pizza place.

The cross section consists of six 12 feet through lanes and a 12.5 feet TWLTL. Both sides have a curb but no sidewalks are provided.

The traffic is composed of about 98% passenger cars and 2% trucks and recreational vehicles.

Buford Highway (north of I-285):

This site extends from 0.1 miles north of Longmire Rd. to a point 0.2 miles north. It is a TWLTL with an AADT of 51,400 and 60 driveways per mile. To the sides of the road you find a small commercial center, a Service Merchandise, a business center, Radio Shack, Pizza Inn, Steak'n Shake, and a Pizza-Inn.

The cross section consists of six 11 feet through lanes and a 12 feet TWLTL. Both sides have a curb but no sidewalks are provided.

The traffic is composed of about 98% passenger cars and 2% trucks and recreational vehicles.

Buford Highway (south of I-285):

This TWLTL site extends from McClave Drive to a point 0.2 miles north. It has an AADT of 38,700 and 90 driveways per mile. To the sides of the road you find a gas station, a motel, a Copper Dollar Saloon, an auto shop, Delta Electronics, a computer store, a small commercial center, Pic-A-Deli Pub, and a contact lens center.

The cross section of this site consists of six 11 feet through lanes and a 14 feet TWLTL. Both sides of the road have a curb but no sidewalks are provided.

The traffic is composed of about 99% passenger cars and 1% trucks and recreational vehicles.

Cobb Parkway (near Windy Hill Road):

This TWLTL site extends from 0.2 miles south of Windy Hill Road to a point 0.2 miles south. It has an AADT of 40,500 and 60 driveways per mile. To the sides of the road you find eight car dealers, three on the west side of the road and five on the east side.

The cross section of this site consists of four 11 feet through lanes and a 14 feet TWLTL. Both sides of the road have a curb but no sidewalks are provided.

The traffic is composed of about 98% passenger cars and 2% trucks and recreational vehicles.

Moreland Avenue:

This site extends from the South River Bridge to a point 0.2 miles south. It is a Raised Median with an AADT of 26,904 and 20 Driveways per mile. It is lined with a truck company on both sides. In this 0.2 mile section there are only four driveways, three on the east side of the road and one on the west side.

The cross section of this roadway is composed of six 12 feet through lanes and a raised median with two left turn bay, one for each direction. Both left turn lanes are 12 feet in width and their lengths are 200 and 400 feet for the north and south sides respectively. No sidewalks are provided.

The traffic is composed of about 85% passenger cars and 15% trucks (two and three axles).

Forest Parkway:

This site is located near the vicinity of Forest Park in Clayton County extending from Old Dixie Highway to Hale Road, or 0.41 miles. It is a Raised Median with an AADT of 25,096 and 62 Driveways per mile. To the sides of this road you find a fast food restaurant, a service station, a car clean up place, 4 car dealers, a used car dealer, an auto body shop, a NAPA auto parts store, a cemetery, a battery service station and a Baptist Church.

The cross section of the site consists of four 12 feet through lanes and a raised median with two left turn bays, one for each direction. Both left turn lanes have a width of 10 feet and a length of approximately 75 feet.

Sidewalks are on both sides of the road as well as street lights, which are approximately every 300 feet.

The traffic is composed of about 95% passenger cars and 5% trucks and recreational vehicles.

Buford Highway:

This site extends from the I-285 off ramp to a point 0.2 miles north. It is a Raised Median with an AADT of 51,409 and 35 Driveways per mile. It is mainly lined with two gas station (one on each side), a fast food restaurant and a small shopping center.

The cross section consists of six 12 feet through lanes and a raised median with two one lane left turn bay. Both left turn lanes have a width of 12 feet and their lengths are 320 feet for the north-bound traffic and 170 feet for the south-bound direction. A sidewalk is provided on the west side of the road.

The traffic is composed of about 95% passenger cars and 5% trucks and recreational vehicles.

Tara Boulevard:

This site is located near the vicinity of Morrow in Clayton County extending from Morrow Industrial Boulevard to a point 0.5 miles south. It is a Raised Median with an AADT of 50,703 and 46 Driveways per mile. To the sides of this road you find three fast food restaurants, two gas stations, a parking lot, a radio store, an auto dealer, a motel and three apartment complex.

The cross section is composed of four 12 feet through lanes and a raised median with two one lane left turn bay. Both left turn lanes are 12 feet in width and have a storage length of about 300 feet. No sidewalks are provided at this site.

The traffic is composed of about 96% passenger cars and 4% trucks and recreational vehicles.

GA-85 (south side):

This site is located inside the limits of the city of Riverdale in Clayton County extending from Roundtree Road to GA-138, or 0.37 miles. It is a Raised Median with an AADT of 36,233 and 91 Driveways per mile. It is mainly lined with a fast food restaurant, a gas station, a furniture store, a residence, an auto parts shop, a sport cycle store, an open lot, an empty building, a Baptist Church, a Beauty College, an office building and a Lube-o-Matic workshop.

The cross section consists of four 12 feet through lanes and a raised median with two one lane left turn bay. Both left turn lanes have a width of 12 feet and their storage length is approximately 120 feet. There are no sidewalks provided at this section.

The traffic is composed of about 96% passenger cars and 4% trucks and recreational vehicles.

Holcomb Bridge Road:

This is one of the pilot sections located in the Atlanta suburb approximately 5 miles north of Sandy Springs. It is a Raised Median with an AADT of 47,970 and 70 Driveways per mile. This section of road is lined with two large shopping centers, 2 restaurants, one bank and 2 gas stations.

The cross section consists of six 12 feet through lanes and a raised median with two one lane left turn bay. Both left turn lanes have a width of 12 feet. No paved sidewalks are present, although a level grassed sidewalk at least 10 feet wide is on both sides of the road.

Fulton Industrial Boulevard:

This site is located to the west side of Atlanta approximately 2 miles west of the perimeter. It extends from Wendell Drive to Martin Luther King Jr. Drive, or 0.3 miles. It is a Raised Median with an AADT of 35,883 and 105 Driveways per mile. To the sides of this road you find 6 fast-food restaurants, a Days Inn motel and a car service station.

The cross section consists of six 12 feet through lanes and a raised median with **NO** left turn bays. A sidewalk is provided on one side of the road.

The traffic is composed of about 93% passenger cars and 7% trucks and recreational vehicles.

DRAFT

Contract Research

GDOT Research Project No. 8602

Final Report

CRITERIA FOR TWO-WAY LEFT-TURN LANES VS. OTHER MEDIANS

Volume II: Accident Comparison of Raised Median and Two-Way Left-Turn Median Treatments

by

Christopher A. Squires, Graduate Student
Peter S. Parsonson, Professor

School of Civil Engineering
Georgia Institute of Technology

Contract with

Department of Transportation
State of Georgia

In cooperation with

U. S. Department of Transportation
Federal Highway Administration

April, 1988

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF CIVIL ENGINEERING
ATLANTA, GEORGIA 30332

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SCHOOL OF
CIVIL ENGINEERING

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April 6, 1988

Mr. Peter Malphurs
State Materials & Research Engineer
Office of Materials and Research
Georgia DOT, 15 Kennedy Drive
Forest Park, GA 30050

Attention: Ms. Sondra Selph, Research & Development Bureau

Dear Mr. Malphurs:

Criteria for Two-Way Left-Turn Lanes Vs. Other Medians
GDOT Research Project No. 8602
Georgia Tech Research Project No. E-20-G03

The purpose of this project is to develop a set of design criteria for the choice between two-way left-turn lanes (TWLTL) and raised-curb medians, considering both capacity and safety.

Transmitted herewith are 10 copies of Volume II of the Final Report. It is the last in the series and is entitled "Accident Comparison of Raised Median and Two-Way Left-Turn Lane Median Treatments." It was produced by our graduate student Chris Squires, under my supervision, as his special research project for the Masters Degree. The data base for this report was state-wide in scope and included 50 TWLTL sections and 32 raised-median sections, each over 0.75 miles in length. This data base was much larger than the one used for the Interim Report submitted to your office by letter of October 13, 1987. Therefore we believe that this present report should supersede and replace the portion of the Interim Report dealing with accident-data collection and analysis.

This report concludes that total accidents per million vehicle miles provide the best indication of relative safety of a median type. For the sections studied, these rates showed raised medians to be safer than TWLTL for both four and six-lane sections. Therefore the selection of type of median, considering safety criteria, clearly favors the raised median design.

Most of the Interim Report was concerned with an introduction to the problem, a review of literature, and extensive research on delay and capacity by our graduate students John Hibbard, Joaquin Vargas and Steve Celniker. That portion of the Interim Report has been separated from the accident-data portion and printed as Volume I of the Final Report.

We are very pleased that we have been able to perform much more work than was contemplated in our agreement, without an increase in budget. This was due to the fact that some of the graduate students involved in the project, particularly Chris Squires, performed their work in fulfillment of course requirements, without charge to our budget.

We hope that you will find this project to have been a good value for your research dollar, and that you will allow us other opportunities in the future to be of some service to your office.

Yours very truly,

Peter S. Parsonson
Professor and Project Director

Acknowledgements

The authors gratefully acknowledge Tim Christian at the Georgia D.O.T. Planning Data Services office in Chamblee for answering questions and putting in a lot of computer time to furnish inventory data required for the project. We also thank Dick Graves of the Traffic and Safety Division for providing accident data. Jim Fincher, also of Traffic and Safety, was especially helpful in guiding our procedure and discussing the significance of our results.

Abstract

It is an accepted fact that the installation of a median will reduce accident occurrence along a previously undivided road. However, choice of a median type is often difficult. Two median treatments in common usage are two-way left-turn lanes (TWLTL) and raised medians. Although a great deal of research has focused on these median treatments, there is still doubt as to the comparative safety of these median types.

The purpose of this report is to provide a comparison of safety of raised medians and TWLTL used as median treatments on four and six-lane roads. (Earlier work in this project compared the delay produced by the two types; the results were presented in an Interim Report dated October, 1987). The objective is to provide a statistical comparison of accident rates for the two sections and develop regression equations to model accident experience for each section. Regression analysis was performed using the Biomedical computer programs (BMDP) statistical software.

Suitable sections of state roads were identified throughout Georgia. Data collection for these sites was accomplished with a combination of field collection and data supplied by the Georgia Department of Transportation. Accident data used in the study covered three years: 1984, 1985 and 1986. The average daily traffic (ADT) for the sections ranged from 9500 to 59,000.

The comparison of accident rates was performed for a variety of conditions. Four and six lane sections were analyzed separately. Midblock accident occurrence was also examined in addition to the total accident rates. Comparisons were made on the basis of accidents per million vehicle miles (MVM) and accidents per mile per year. As a point of reference, injury accidents were also compared. It was concluded that total accidents per MVM provide the best indication of relative safety of a median type. For the sections studied, these rates showed raised medians to be safer than TWLTL for both four and six lane sections.

Sixteen regression equations were created to model conditions similar to those of the accident comparison. Equations were developed for raised median and TWLTL sections, four and six lane sections, total and midblock accidents, and accidents per MVM and accidents per mile per year. From the regression equations, tables of expected accident rate values were developed. Conclusions from these tables are based on total accidents per MVM for four and six lane sections. The tables indicated that for four-lane sections, raised medians had a lower accident rate over the range of data studied. Results from six-lane sections were somewhat more complicated. The tables indicated that raised medians would be safer for most conditions. TWLTL had a lower accident rate when the number of driveways per mile is high, the number of signals per mile is low, and the number of approaches per mile is low.

For the most part, results compared favorably with previous research. It was necessary to perform these comparisons on the same terms as the original study. This usually meant using accidents per mile per year along four-lane sections as an indicator of safety, rather than accidents per MVM over all of the sites.

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Chapter 1:
Introduction

This study is intended to provide a basis of comparison between two alternative median treatment types frequently used on arterial roads. Both raised medians and continuous two-way left-turn lanes (TWLTL) are often used on busy four and six lane roads. Implementing either type of median treatment will reduce the number of accidents experienced on an undivided road. This study compares the relative safety of these two median treatments.

A TWLTL is a lane in the center of a road dedicated to left turns by both directions of traffic. TWLTL provide excellent service to the land adjoining a roadway. They provide an area for deceleration and stopping prior to a left turn off of the road. By providing such an area, TWLTL reduce the frequency and severity of rear-end conflicts. They grant additional perception time to drivers making left-turns. They are also used by cars turning onto the road as they accelerate up to speed. TWLTL allow more flexible use of the entire roadway. For instance, temporary work zones can easily be established.

Raised medians facilitate the movement of through traffic along a roadway. Turning movements are concentrated at planned points where they can be accommodated. This concentration reduces the basic number of conflict points for vehicles turning onto or off of the roadway. There is also a reduction in the number of types of driveway manuevers. Raised medians may also be used for their aesthetic qualities.

The purpose of the study is to provide a quantitative basis for determining whether raised medians or TWLTL are safer for a given situation. In order to facilitate this objective, as many sites as possible were identified. The sites were located throughout the state of Georgia. All of the sites were visited in order to determine their suitability and to collect data. The Georgia Department of Transportation provided all of the information which could not be readily collected in the field.

The study was limited to roads with either four or six travel lanes. Data for these two site-types were analyzed independently. Accident data was obtained for injury, and all accidents occurring along a section. Full data analysis was performed for both total and midblock accident occurrence.

The research included a review of previous research, location of sites, collection of site data, statistical analysis of data, development of regression equations to model data, and a comparison with other research results.

Chapter 2:
Previous Research

Since this study was directly linked with a similar project by Joaquin Vargas (1), no literature review, per se, was conducted. A brief summary of the previous research is provided here. For a more detailed review, the Vargas report should be referenced.

An FHWA report by Glennon (2) advocated the use of either TWLTL or raised medians to reduce accidents and delay caused by an undivided roadway. Accident reductions from the undivided highway condition were predicted. Comparing the reductions for raised medians and TWLTL implies that TWLTL would be safer for low and moderate levels of development (measured as having fewer than 60 commercial driveways per mile). Raised medians would be considered safer for high levels of development. The relative safety of the two median types remained constant for all ADT levels studied (less than 5,000, 5,000 to 15,000, and above 15,000).

Glennon also had general comments about each median type. The attractiveness of a TWLTL is the removal of left-turning vehicles from through traffic while still providing maximum left-turn access. TWLTL should be used, in lieu of an undivided road, when there are frequent rear-end conflicts caused by left turning vehicles. They are used on moderate to high-volume highways which have a low number of cross streets and a high number of driveways.

The report went on to say that raised medians eliminate severe conflicts from all minor driveways. Also, there will be a reduction of conflicts at major driveways. However, there will be some increase in conflicts because of indirect left-turn manuevers used to move vehicles to minor driveways. Raised medians are used on major arterials with a moderate to high number of driveways per mile. A cross-street spacing of one-half mile or greater is desired.

Perhaps the most quoted report, to date, has been Martin Parker's Virginia study (3). The study produced regression equations for the accident occurrence of raised median, traversable median (including TWLTL), and undivided highway sections. In addition to the development of regression equations to model accident occurrence, Parker presented general guidelines for the implementation of the various median types. The report said that if stopping sight distance is less than AASHTO standards, a TWLTL should not be used. A raised median should not be used where speeds exceed 45 mph unless the curb face is mountable. Raised medians are desirable when access points are limited to major intersections, there are large pedestrian volumes, or a grid pattern permits circuitous flow of traffic without disrupting residential traffic. Additionally, TWLTL should not be used when access is required on only one side of the street in question.

Douglas Harwood (4) listed characteristics and appropriate implementations of raised medians and TWLTL. Raised medians discourage new strip development. However, they increase travel time for vehicles desiring to turn left where median openings are not provided. They also reduce operational flexibility, such as emergency vehicle operations, lane closures, or work zones. Raised medians are best suited for use on major arterials with high volumes of through traffic and limited access points. They are also appropriate when a highway agency makes a conscious choice to favor the traffic movement function through an area. He went on to say that two-way left-turn lanes reduce delay to left-turning vehicles. They enhance operational flexibility. However, they do not provide any refuge area for pedestrians. Also the inappropriate use of TWLTL by drivers may cause vehicular conflicts. They may encourage strip development. They should be used when there are low to moderate volumes of through traffic.

Several reports, including Hoffman (5), Nemeth (6), McCormick (7), and Thakkar (8), have been written comparing TWLTL with undivided roads. All of this research indicated that TWLTL were preferable to an undivided road. However, these reports did not indicate whether a TWLTL would be preferable to a raised median.

Chapter 3:
Data Collection

Site Selection

Sites were chosen to fit into one of four catagories: TWLTL with 4 or 6 through lanes or Raised Median with 4 or 6 through lanes. Other than the following restrictions, there were no preconceived ideas about the range of data to be expected from these sites. The parameters used for selection were:

- ADT $\geq$ 9500
- Be on a State Route
- Have a constant 4 or 6 through lanes
- Free access to the road at grade (Uncontrolled access)

It was desired to keep ADTs above 9500 and have free access to the road in order to insure that the study incorporated only urban type sections. Sites located on a State Route were necessary to obtain accurate accident data.

Many of the sites chosen were suggested by the earlier work of Joaquin Vargas. All of the remaining sites were found through computer searches of the Georgia D.O.T. road inventories. The inventories provided the preliminary information needed to identify sites including number of through lanes, ADT, access control, type of median treatment, and lane widths.

The initial search for sites was confined to the metropolitan Atlanta area for the sake of convenience. The area included in the search was limited to Fulton, Dekalb, Cherokee, Clayton, Cobb, Gwinnett, and Rockdale counties. This area provided an adequate number of TWLTL sites. However, only four Raised Median sites were identified. Several potential sites had to be eliminated because of the use of a depressed median in some areas instead of a continuous raised median. The search for sites was then broadened to include all of Georgia. From this search, fifteen additional Raised Median sites were found. Also, the number of TWLTL sites increased from sixteen to twenty.

The twenty TWLTL sites have a total length of 74.86 miles. The nineteen Raised

Median sites have a total length of 47.60 miles. Each of these sites was subdivided into sections to the fullest extent possible. Sections were created to have a length greater than 0.75 miles. This was necessary to insure that the data for all of the sections would be representative of actual conditions. Short sections length tend to produce highly fluctuating data. It was also desired to define the sections so that ADT values would remain constant through the section. Keeping the ADT constant was a secondary consideration to maintaining an adequate section length.

SITE DESCRIPTION

Table 3.1 provides a summary of basic site and section characteristics. Table 3.2 lists the location of the sites used in the study. The mileage indicators were used to reference the sites to Georgia D.O.T. road inventories and accident data. In addition to the site summary, an extended site description is given in Appendix A.

Table 3.1: Site and Section characteristics

	TWLTL	Raised Medians
Number of Sites		
4 Lane sections	17	13
6 Lane sections	3	6
Totals	20	19
Number of Sections		
4 Lane sections	42	15
6 Lane sections	8	17
Totals	50	32
Site Lengths		
4 Lane sections	62.48	24.68
6 Lane sections	12.38	22.92
Totals	74.68	47.60
Million Vehicle Miles per year		
4 Lane sections	691.48	228.25
6 Lane sections	149.05	264.42
Totals	840.53	492.68

Table 3.2: Site Location Summary

Site	SR No.	County	Begin Mile	End Mile	Thru Lanes
TWO-WAY LEFT-TURN LANES:					
T1	3	Cobb	1.92	7.12	4
T2	3	Cobb	7.31	7.80	4
T3	3	Cobb	8.12	9.29	4
T4	9	Fulton	19.38	20.69	4
T5	9	Fulton	6.41	17.61	4
T6	54	Clayton	8.22	13.49	4
T7	3	Clayton	11.69	14.42	4
T8	85	Clayton	3.44	4.64	4
T9	279	Fulton	0.24	5.01	4
T10	155	Dekalb	7.70	11.28	4
T11	10	Dekalb	5.67	9.86	6
T12	10	Gwinnett	0.56	12.90	4
T13	13	Dekalb	0.00	6.75	6
T14	13	Dekalb/Gwinnett	7.74(Dekalb)	2.35(Gwin.)	4
T15	42	Dekalb	3.60	4.96	4
T16	26	Bulloch	19.06	20.30	4
T17	121	Richmond	13.54	14.98	6
T18	28	Richmond	7.32	10.76	4
T19	52	Whitfield	0.19	1.86	4
T20	141	Dekalb	2.26	4.88	4
RAISED MEDIANS:					
R1	140	Fulton	6.82	8.24	6
R2	331	Clayton	1.23	3.31	4
R3	42	Dekalb	0.70	3.55	4
R4	11	Bibb	14.96	16.87	4
R5	22	Bibb	11.69	13.47	4
R6	204	Chatham	15.75	21.47	6
R7	204	Chatham	21.47	23.21	4
R8	21	Chatham	11.43	13.04	4
R9	26	Chatham	18.34	21.74	4
R10	26	Bulloch	17.86	18.99	4
R11	4	Richmond	16.96	20.73	6
R12	121	Richmond	10.12	13.46	6
R13	28	Richmond	3.81	4.67	4
R14	52	Whitfield	2.52	4.32	6
R15	85	Muscogee	3.43	4.82	4
R16	1	Muscogee	2.68	6.70	6
R17	1	Muscogee	6.70	7.70	4
R18	1	Muscogee	8.90	12.82	4
R19	141	Dekalb	5.37	7.23	4

DATA COLLECTED

Data for the sections were obtained from three sources:

- Road inventories from Ga. D.O.T. Planning Data Services
- Field collection
- Accident data from Ga. D.O.T. Traffic and Safety Division

Road inventories provided ADT and mileage points accurate to one one-hundredth of a mile. These were used to subdivide sites into sections.

The accident data were obtained in summary form showing fatal accidents, injury accidents, and total accidents for each section. Additionally, this data was provided for the total length of the section and for midblock portions of the section. Accident data were available for 1984, 1985, and 1986 on all sites except T18 and R13, each of which had only two years of data.

Data collected in the field for each section consisted of the number of driveways, signalized intersections, unsignalized approaches (streets), and, for Raised Median sections, median openings other than at signalized intersections.

DATA SUMMARY

The accident data obtained from the Georgia D.O.T. were used to calculate accidents per million vehicle miles and accidents per mile per year. Accidents per million vehicle miles was felt to be the best indicator for comparison between median types. This was true because of the great variation of ADT present in the sites used. However, accidents per mile per year has been calculated for use in comparing this study with other research.

Table 3.3 provides a summary of the accident calculations. The accident rates for each section are shown in Appendix B. Accident rates were calculated for injury accidents, and all accidents (called simply "accidents"). There was no determination made of the number of injuries associated with each section as these numbers are dependent on too many variables outside of the scope of this research.

The summary rates presented in the table were not obtained by averaging the accident rates for individual sections. This would have created an error as the site lengths and ADTs vary. Instead, accidents per MVM were obtained for each section type by summing the number of accidents per year and then dividing that number by the total number of million vehicle miles (MVM) traveled per year. Accidents per mile per year were found by dividing the same accidents per year figure by the sum of section lengths for the section type.

Table 3.3: Summary of Accident Data

	Total Accidents			Midblock Accidents		
	TWLTL	RM	% Diff	TWLTL	RM	% Diff
Accidents / MVM						
4 Lane sections	8.99	7.67	-14.7%	3.50	1.34	-61.7%
6 Lane sections	10.82	8.15	-24.7%	4.19	1.92	-54.2%
Accidents / Mi / Yr						
4 Lane sections	99.45	70.91	-28.7%	38.78	12.39	-68.1%
6 Lane sections	130.26	94.07	-27.8%	50.46	22.13	-56.1%
Injury Accidents / MVM						
4 Lane sections	2.00	1.70	-15.0%	0.81	0.32	-60.5%
6 Lane sections	3.61	1.90	-47.4%	1.09	0.43	-60.6%
Injury Accidents / Mi / Yr						
4 Lane sections	22.14	15.76	-28.8%	8.91	2.92	-67.2%
6 Lane sections	43.46	21.87	-49.7%	13.14	4.93	-62.5%
Fatal Accidents / MVM						
4 Lane sections	0.01	0.03	-66.7%	0.01	0.01	0.0
6 Lane sections	0.03	0.03	0.0	0.02	0.01	-50.0%
Fatal Accidents / Mi / Yr						
4 Lane sections	0.14	0.29	-51.7%	0.06	0.08	-25.0%
6 Lane sections	0.38	0.39	-2.6%	0.30	0.10	-66.7%

The determination of summary accident rates has led to a dissimilar weighting for the two median types. Accidents per mile per year are weighted on the basis of sum of section lengths for each type. The weighting was incurred from the relative section lengths. For raised medians the rates for four lane sections are weighted 1.1 times the six lane rates. For TWLTL, the weighting is far more unequal because of the long four-lane section length relative to the short six-lane section length. The four-lane section rates have 5.0 times the weight of six-lane section rates. Accidents per MVM are treated similarly. Weighting for these rates is affected on the basis of MVM per year. Again, raised median sections have a nearly equal weight: six-lane section rates are weighted 1.2 times four-lane section rates. TWLTL rates are again heavily in favor of four-lane sections as they are weighted 4.6 times those of six-lane sections.

As can be seen from the table, four-lane rates are lower than six-lane rates. Because of the dissimilar weighting between median types, TWLTL rates for all sections are not going to be as high relative to raised medians. This has the effect of producing a lower percentage difference for the rates of all of the sections than might be expected by viewing the four and six lane rate differences.

The data obtained from road inventories and field collection were converted to a per mile basis (Signals per mile, for instance). These are listed for each section in Appendix C. Table 3.4 summarizes the data. Again, the data is separated by section type.

Table 3.4: Summary of Site Data

		TWLTL		RAISED MEDIAN	
		6 Lane	4 Lane	6 Lane	4 Lane
ADT	Minimum	23712	9500	20360	10180
	Maximum	47685	52240	47180	59070
	Mean	32769	30542	31994	24605
	Stnd Dev.	8308	9881	7969	10866
Drives/mi	Minimum	36.90	10.08	18.18	5.00
	Maximum	144.34	103.53	106.40	76.74
	Mean	71.29	50.16	45.62	33.75
	Stnd Dev.	33.96	21.67	22.84	19.30
Signals/mi	Minimum	1.07	0.00	0.00	0.00
	Maximum	5.66	7.06	4.76	8.14
	Mean	2.63	2.10	2.25	2.26
	Stnd. Dev.	1.54	1.56	1.08	1.97
Openings/mi	Minimum	---	---	0.00	1.14
	Maximum	---	---	7.43	13.79
	Mean	---	---	2.89	3.98
	Stnd. Dev.	---	---	1.91	3.37

Data obtained has been plotted in the form of scatter diagrams. Each of the independent variables is plotted against accidents per MVM and against accidents per mile per year for each of the section types. These are included in Appendix D. The scatter diagrams are perhaps more informative about the data than the statistics listed above.

Four of the scatter diagrams are reproduced on the following pages. From the diagrams, a lack of Raised Median data is evident. As shown in Figure 3.1 below, no four lane raised median sites with an ADT between 30,000 and 59,000 were identified. Also, Figures 3.1 and 3.2 illustrate the difference between midblock accidents per MVM and midblock accidents per mile per year. Accidents per mile per year, plotted in Figure 3.1, show one point, section R19 with 56 accidents per mile per year, to have accidents far above any other section. However, Figure 3.2 plotting accidents per MVM, shows the same section to have a rate similar to the other sections.

Another interesting problem with the data is evident from Figures 3.3 and 3.4. Figure 3.3 seems to indicate that, for midblock accidents, one of the points, section T1A, is an outlier. However, as can be seen in Figure 3.4, this site fits in with the total accident data. Several other sections, including T2, T3, T5D, T5E, R2B, R4, R7, and R15, also have midblock accident rates which are inconsistent with total accident rates for those sections. Most likely, midblock accidents are dependent on more variables than are included in this study.

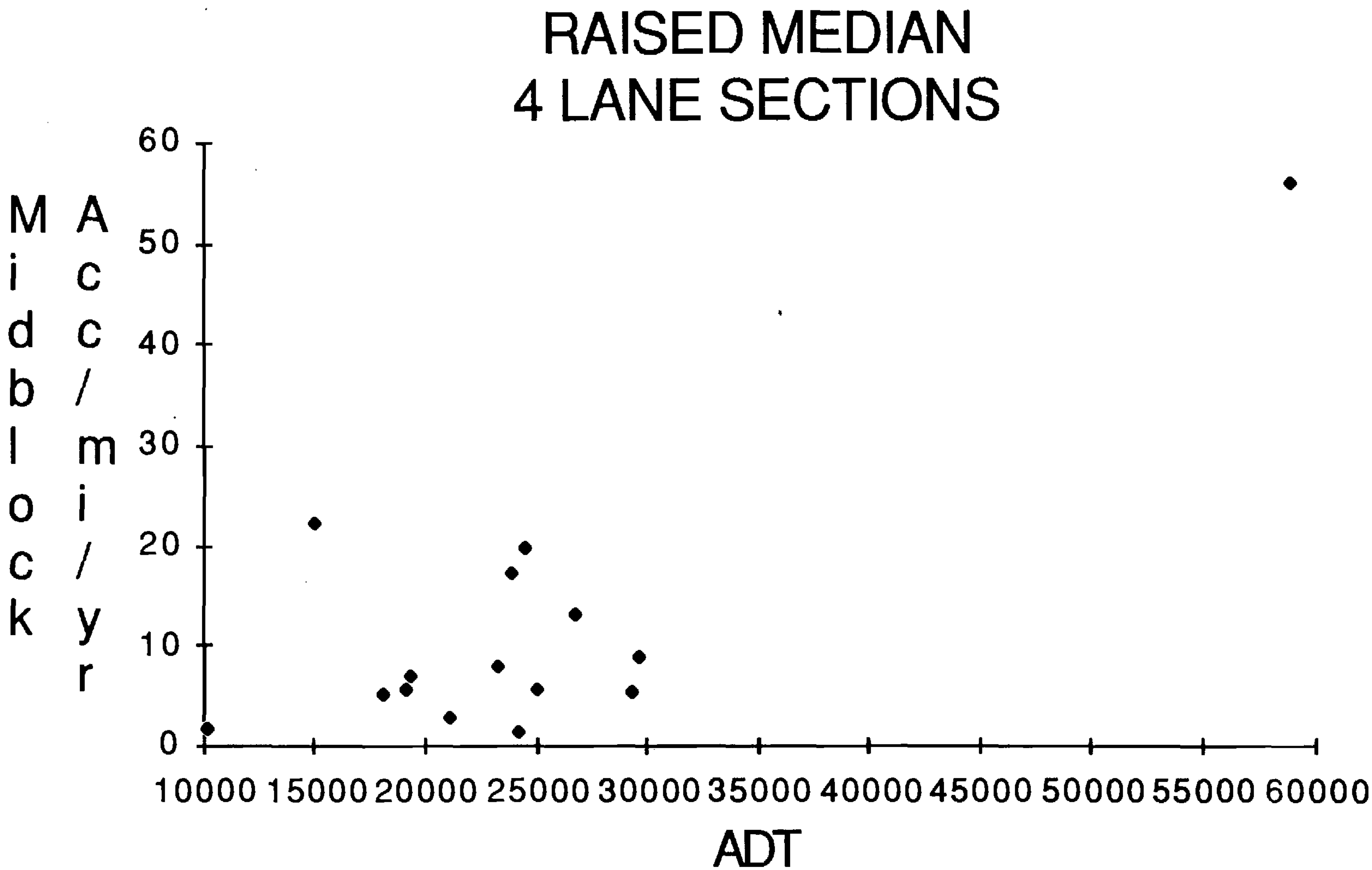

Figure 3.1: Scatter Diagram - Raised Median Four Lane Sections
Midblock Accidents per mile per year

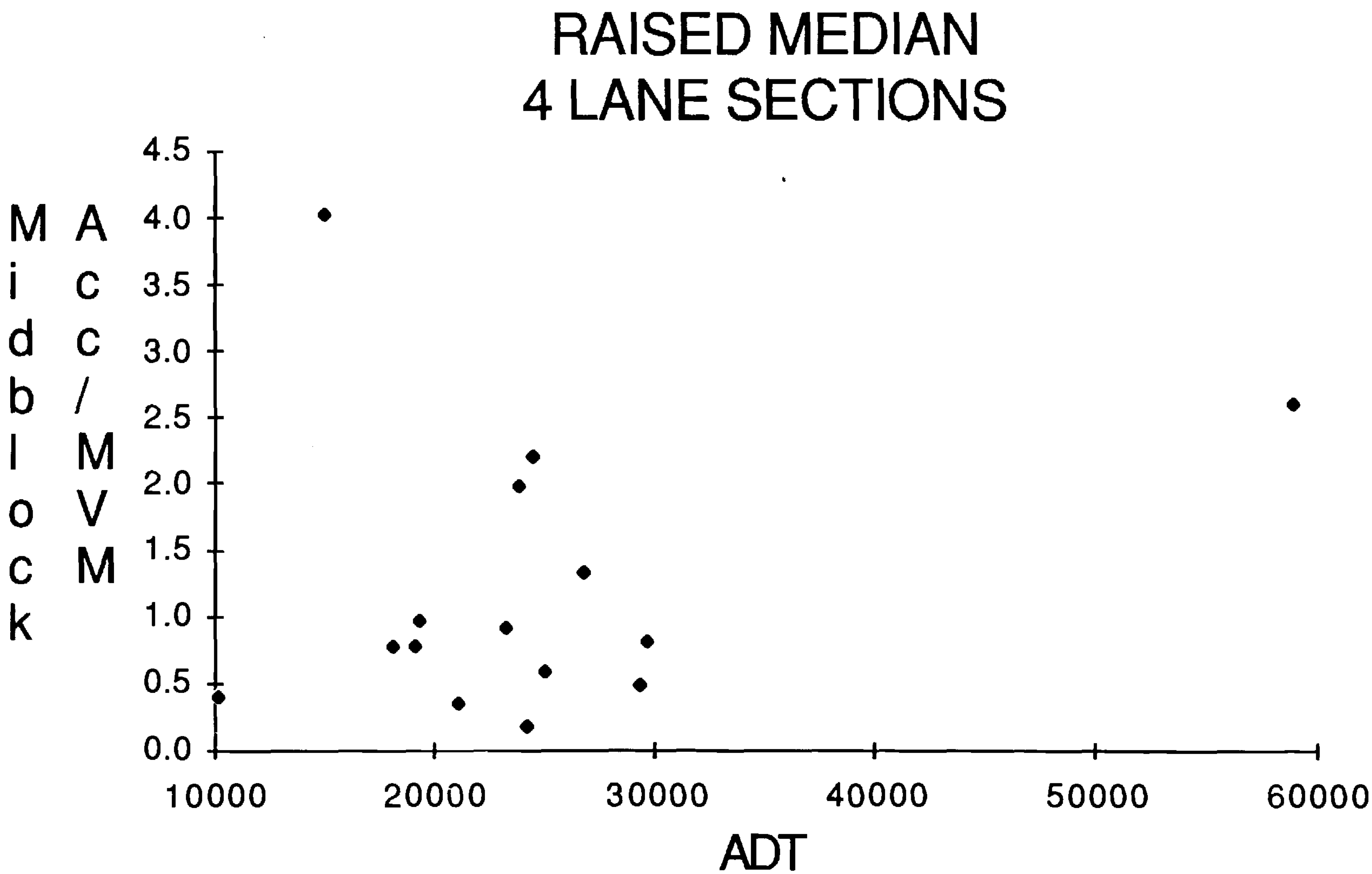

Figure 3.2: Scatter Diagram - Raised Median Four Lane Sections
Midblook Accidents per million vehicle miles

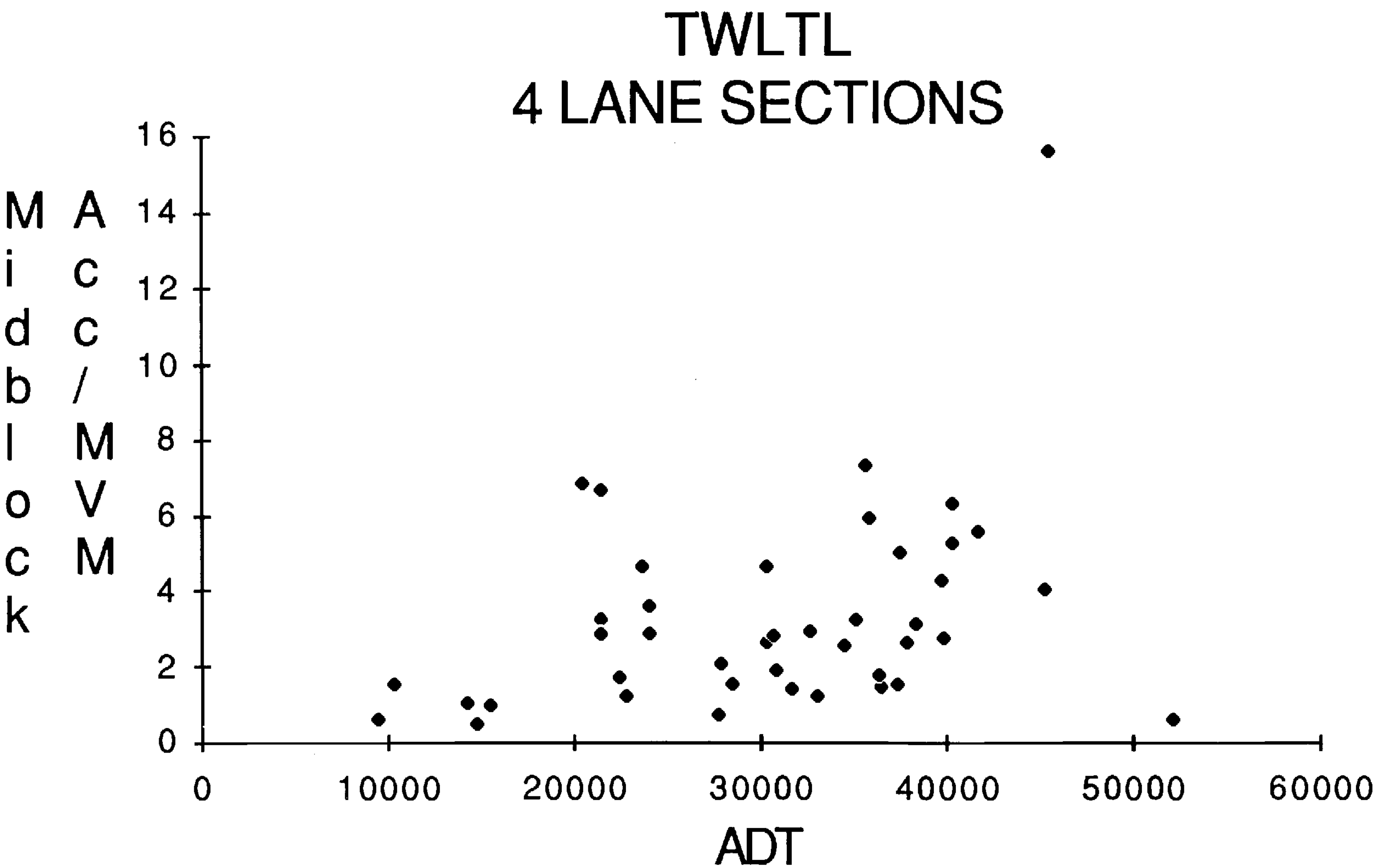

Figure 3.3: Scatter Diagram - TWLTL Four Lane Sections
Midblock Accidents per million vehicle miles

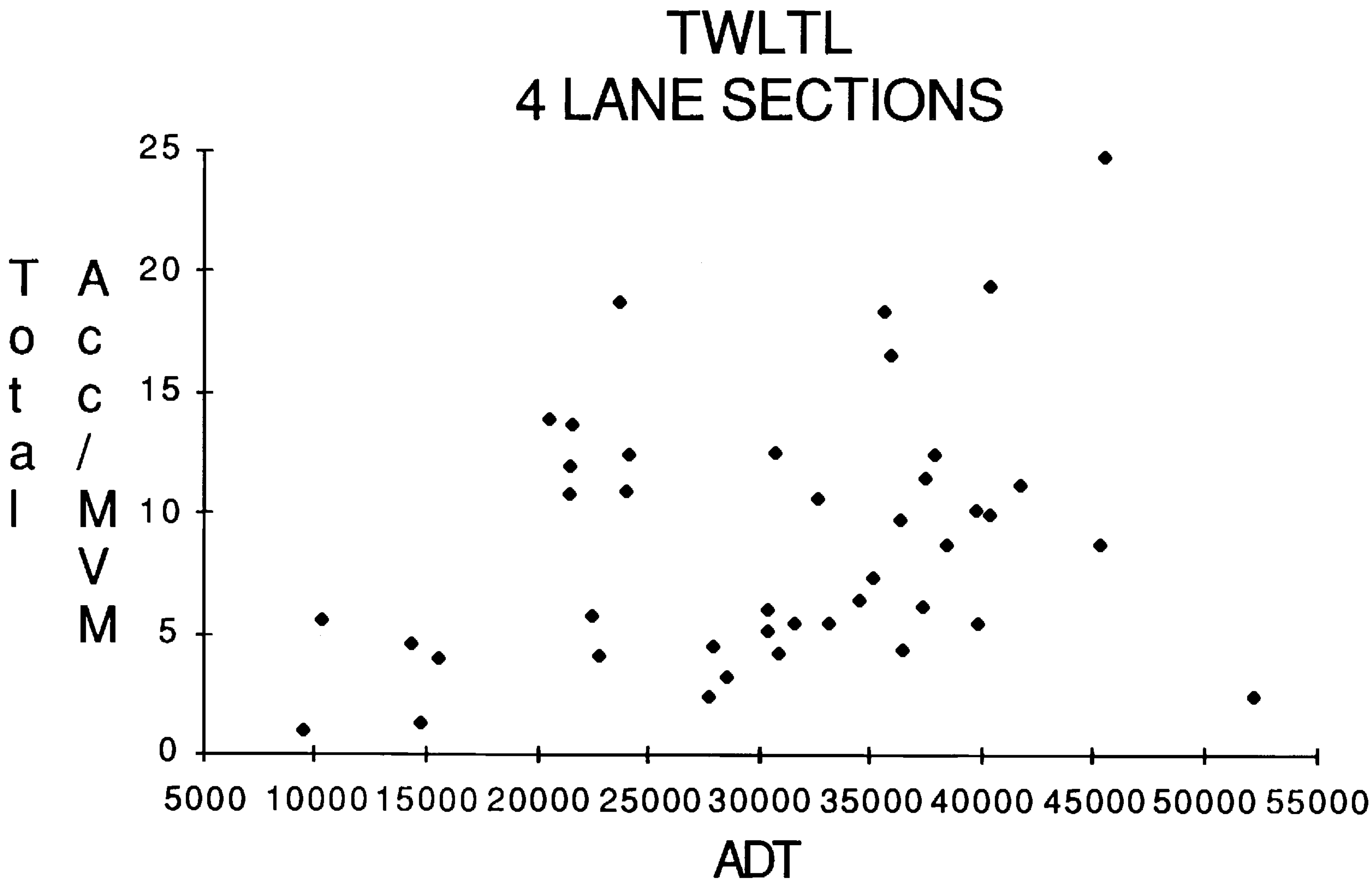

Figure 3.4: Scatter Diagram - TWLTL Four Lane Sections
Total Accidents per Million vehicle miles

Chapter 4:
DATA ANALYSIS and RESULTS

COMPARISON OF ACCIDENT RATES

The accident data were tested to find at what error level there was a significant difference between two-way left-turn lane accidents and Raised Median accidents. Table 4.1 lists the alpha error at which the two accident rates are significantly different. The column labled "Lower Acc. Rate" designates which median type has the lower accident rate in question. The last two columns on the right also indicate whether or not the two rates are significantly different at alpha values of 0.10 and 0.05.

Calculations are based on a one-sided student T distribution. The assumption that $\mu_T = \mu_{RM}$ (mean of TWLTL accidents equals mean of raised median accidents) was tested. With the initial hypothesis, any difference in accident rates is due to chance alone. The alternate hypothesis, for which the alpha error has been calculated, states that the difference in rates is not attributable to chance alone and that the means are significantly different.

Since the t-test was one sided, the alpha error for any difference in rates can vary between 0.0001 and 0.5000 (rounded up). Alpha-errors can also be stated in terms of confidence intervals/ An error of 0.3000, for example, indicates that there is a 70% confidence interval that there is a significant difference between rates.

One can never be certain, statistically speaking, that rates of finite sample sizes are definitely different. However, some of the extremely low alpha errors are as close as one could reasonably expect to get to being absolutely certain of a difference in rates.

Caution should be used in interpreting some of the differences in Table 4.1. Rate comparisons for injury and fatal accidents should be viewed in conjunction with the actual rates shown in the accident rates summary (Table 3.3). Rates for these accidents are extremely low, making them statistically unstable. With such a rare occurrence, as fatal accidents appear to be, the occurrence of just a few additional accidents would drastically affect the difference in rates.

Table 4.1: Significant Difference of Accident Rates between TWLTL and Raised Medians

Section type	Accident type	Lower Acc. Rate	Alpha-error at point of significant difference	Significant difference at alpha-error =0.10	=0.05
Total Accidents					
4 Lane sections	Acc/MVM	RM	0.2168	no	no
	Acc/mile/yr	RM	0.0980	yes	no
6 Lane sections	Acc/MVM	RM	0.0549	yes	no
	Acc/mile/yr	RM	0.0883	yes	no
Midblock Accidents					
4 Lane sections	Acc/MVM	RM	0.0009	yes	yes
	Acc/mile/yr	RM	0.0128	yes	yes
6 Lane sections	Acc/MVM	RM	<0.0005	yes	yes
	Acc/mile/yr	RM	0.0224	yes	yes
Total Injury Accidents					
4 Lane sections	Acc/MVM	RM	0.2016	no	no
	Acc/mile/yr	RM	0.0973	yes	no
6 Lane sections	Acc/MVM	RM	0.0052	yes	yes
	Acc/mile/yr	RM	0.0334	yes	yes
Midblock Injury Accidents					
4 Lane sections	Acc/MVM	RM	0.0043	yes	yes
	Acc/mile/yr	RM	0.0231	yes	yes
6 Lane sections	Acc/MVM	RM	<0.0005	yes	yes
	Acc/mile/yr	RM	<0.0005	yes	yes

(continued on next page)

Table 4.1 continued

Section type	Accident type	Lower Acc. Rate	Alpha-error at point of significant difference	Significant difference at alpha-error =0.10	=0.05
Total Fatal Accidents					
4 Lane sections	Acc/MVM	TWLTL	0.0028	yes	yes
	Acc/mile/yr	TWLTL	0.0099	yes	yes
6 Lane sections	Acc/MVM	No difference:	Rates were equal		
	Acc/mile/yr	TWLTL	0.49	no	no
Midblock Fatal Accidents					
4 Lane sections	Acc/MVM	No difference:	Rates were equal		
	Acc/mile/yr	TWLTL	0.316	no	no
6 Lane sections	Acc/MVM	RM	0.171	no	no
	Acc/mile/yr	RM	0.0385	yes	yes

It is readily apparent that raised medians were always safer in terms of the number of midblock accidents. However, for many reasons, this should not be a decisive factor in comparison of the two median types. Raised medians shift many conflicts from midblock locations to surrounding intersections. Also, conceptually, minimizing total accidents, not just midblock accidents, should be important in comparing the effects of median type.

A comparison of accident rates should be based on the total number of accidents, accepting the provision that injury and fatal accidents are not good statistical indicators. Also, as mentioned earlier, accidents per million vehicle miles (MVM) are prefered to accidents per mile per year. The use of the accident per MVM rate accounts for differences in traffic volumes among sites.

This reduces the most useful comparisons to those of total accidents per MVM for four and six lane sections. As can be seen, the rates still indicate that raised medians are, in general, safer than TWLTL for the range of variable data tested. However, the question of determining an acceptable alpha error is important in assessing significance to the difference in four-lane accident rates.

REGRESSION MODELS

Regression equations were developed to model data obtained for each section type. Four basic section types were used (Raised median and TWLTL each with four and six lane sections). Additionally, data was further subdivided by total and midblock accidents and accidents per MVM and accidents per mile per year. This created sixteen regression models.

Regression equations were found by using BMDP statistical software on the Georgia Tech mainframe computer (Cyber B). Three programs were used. Data was initially tested with BMDP9R and BMDP2R to determine which variables were significant in the regression. BMDP1R was then used to find the final regression equation based on the variable sets found by the first two programs. Appendix E presents a detailed account of the interaction with Cyber B required to use these programs. The appendix also gives part of an example output from the BMDP1R program.

BMDP9R is an "all-possible-subset" regression program, meaning that the program will test all of the possible combinations of data from single variables up to all of the independent variables. The best set of variables is then chosen from the tested combinations on the basis of Mallow's C_p.

This statistic provides a measure of whether the regression equation has enough information in it. Ideally, C_p would equal the number of variables in the equation (designated as p). If $C_p > p$, there is valuable information left out of the equation. Conversely, if $C_p < p$, there are too many variables in the equation. Use of this indicator serves to maximize both the squared multiple correlation (R^2) and the F Ratio (also called F-Statistic). Neither of these statistics, when used individually, gives an accurate description of an equation's value. While it is desired to maximize R^2, excess variables in an equation tend to inflate this figure. While the F Ratio does not describe the relationship between the regression and residual sum of squares, as R^2 does, this statistic reacts inversely with the addition of unnecessary variables. The F Ratio is used with the R^2 statistic to find the best regression equation.

BMDP2R was then employed to find what it considered to be the best set of variables. BMDP2R is a stepwise regression program. This means that the program attempts to enter a variable into an equation and then seeks to remove a variable. Quite often, this results in a smaller variable list than would be suggested by other programs. In fact, for four out of the sixteen models, BMDP9R and BMDP2R differed in their suggested variable list.

All of the suggested variables combinations were then used with BMDP1R in order to find the final regression equation for that section type. BMDP1R is a multiple linear regression program. When alternate variable lists were compared, the equation which produced the best combination of R^2 and F ratio was chosen.

Table 4.2 lists the variables tested for each section type, along with the corresponding R^2 and F Ratio values. In the cases where two variable sets are listed for one section, such as TWLTL six lane section accidents per mile per year, the set listed as number one is the basis for the final regression equation.

Table 4.2: Variable sets used for Regression with R^2 and F Ratio values

Section type		Variable sets	Multiple R^2	F Ratio
TOTAL ACCIDENTS				
TWLTL 6 Lanes -Acc/mi/yr	1)	ADT, Drives/mi, Signals/mi, Apprch/mi	0.9861	53.088
	2)	ADT, Signals/mi	0.8940	21.076
-Acc/MVM		Signals/mi, Appch/mi, Drives/mi	0.9572	29.823
TWLTL 4 Lanes -Acc/mi/yr	1)	ADT, Signals/mi, Apprch/mi	0.6018	19.146
	2)	ADT, Drives/mi, Signals/mi, Approach/mi	0.6328	15.941
-Acc/MVM	1)	Signals/mi	0.4443	31.980
	2)	Drives/mi, Signals/mi, Approach/mi	0.5538	15.720
R. Med. 6 Lanes -Acc/mi/yr		ADT, Signals/mi	0.6242	11.629
-Acc/MVM		Signals/mi	0.2639	5.378
R. Med. 4 Lanes -Acc/mi/yr		ADT, Signals/mi	0.7670	19.752
-Acc/MVM		Signals/mi	0.7990	51.661
MIDBLOCK ACCIDENTS				
TWLTL 6 Lanes -Acc/mi/yr		ADT	0.8294	29.167
-Acc/MVM		ADT	0.6281	10.131
TWLTL 4 Lanes -Acc/mi/yr		ADT, Drives/mi, Apprch/mi	0.4772	11.563
-Acc/MVM		Drives/mi, Apprch/mi	0.3939	12.671
R. Med. 6 Lanes -Acc/mi/yr		ADT	0.2768	5.741
-Acc/MVM		Openings/mi, Signals/mi	0.0749	0.567
R. Med. 4 Lanes -Acc/mi/yr	1)	ADT, Signals/mi	0.7579	18.781
	2)	Signals/mi, Appch/mi, Openings/mi	0.2130	0.993
-Acc/MVM		Drives/mi, Signals/mi	0.7175	15.236

As can be seen from Table 4.2, regression equations were found that fit total accidents well for almost all section types. Raised median six lane section accidents per

MVM were the exception to this. On the other hand, half of the midblock accident models fit poorly. This indicates that the type of data obtained was not adequate to explain midblock accidents.

Regression equations developed are linear. That is, they are of the form: $y = aX_1 + bX_2 + ... + f$. Table 4.3, on the following page, lists regression coefficients for their respective variables.

As can be seen from the table, all of the total accident equations rely on the number of signals per mile. Further, all of the total accident per mile per year equations(and none of the total accident per MVM equations) incorporate ADT.

Somewhat unexpectedly, only TWLTL six lane sections utilized the number of driveways per mile. The coefficients are believed to have been included as negative values in order to counter the partially additive effects of other variables in the equation. The same might be said for the number of approaches per mile coefficient for the TWLTL four lane sections accident per mile per year equation.

Table 4.3: Regression Coefficients

Total Accidents

Section	Accident Type	ADT	Coefficients: Drives per mi	Signals per mi	Apprch per mi	Open. per mi	Constant
TWLTL 6 Lanes	Acc/Mi/Yr	0.0050848	-0.89517	32.37220	6.48221	- - -	-73.91125
	Acc/MVM	0	-0.08593	3.08711	0.44833	- - -	7.53150
TWLTL 4 Lanes	Acc/Mi/Yr	0.0038777	0	22.68622	-8.85380	- - -	-21.86862
	Acc/MVM	0	0	2.29131	0	- - -	4.01780
Raised Median 6 Lanes	Acc/Mi/Yr	0.00455	0	22.46702	0	0	-96.48022
	Acc/MVM	0	0	1.96196	0	0	3.85559
Raised Median 4 Lanes	Acc/Mi/Yr	0.0019168	0	16.13910	0	0	-14.79288
	Acc/MVM	0	0	2.72091	0	0	1.91835

Midblock Accidents

Section	Accident Type	ADT	Coefficients: Drives per mi	Signals per mi	Apprch per mi	Openings per mi	Constant
TWLTL 6 Lanes	Acc/Mi/Yr	0.0033571	0	0	0	- - -	-60.86993
	Acc/MVM	0.0001292	0	0	0	- - -	-0.36498
TWLTL 4 Lanes	Acc/Mi/Yr	0.0016209	0.52512	0	-8.74647	- - -	4.19088
	Acc/MVM	0	0.05632	0	-0.61905	- - -	3.29801
Raised Median 6 Lanes	Acc/Mi/Yr	0.0009661	0	0	0	0	-8.13549
	Acc/MVM	0	0	0.16643	0	-0.10956	1.86028
							-19.32438
Raised Median 4 Lanes	Acc/Mi/Yr	0.0010357	0	2.51833	0	0	0.98599
	Acc/MVM	0	-0.04567	0.78479	0	0	

EXPECTED VALUE TABLES

From the regression equations, tables of expected accident rates were created. These tables list the accident rates predicted by the regression equations. The full set of tables are shown in Appendix F. The tables cover only data ranges which were present at the sections studied. This has led to different variables value ranges between four and six lane sections. For instance, ADTs range from 20,000 to 50,000 for six lane sections while four lane section ADTs range from 10,000 to 50,000.

However, in some places, the tables give rates at combinations of independent-variable values which were not covered by the sections used in this study. The table of expected four-lane section accidents per MVM has no rates which were not covered by the data obtained. This results from the limited number of independent variables found to be significant in the corresponding regression equations. On the other hand, the table for six lane accidents per MVM has several areas which were not found in the study sections. In this table, all of these were predicted TWLTL rates. This has occurred because of the scarcity of TWLTL six lane sections. For all values of ADT, these areas are:

- -One signal per mile, 30 drives per mile, and six approaches per mile
- -One signal per mile, 60 drives per mile, and four or six approaches per mile
- -One or two signals per mile and 90 drives per mile
- -Two signals per mile, 30 drives per mile, and four or six approaches per mile
- -Three signals per mile and 30 drives per mile
- -Three signals per mile, 60 drives per mile, and six approaches per mile
- -Three signals per mile, 90 drives per mile, and four or six approaches per mile

All of the tables use the same variable format even if some of the variables do not affect the accident rate. This is done to facilitate comparisons and promote clarity. An exception is the table showing midblock accidents per MVM expected for six lane sections which was altered to incorporate the number of openings per mile.

The tables present a great amount of data which bears scrutiny. The purpose of the tables is not to show an absolute accident rate, rather they are intended to show trends in the data and the relative difference between median types.

Two tables from that appendix are reproduced here. Tables 4.4 and 4.5 present the expected total accident per MVM for four and six lanes, respectively. Table 4.4 shows raised medians to be safer than TWLTL over the range of data studied for four lane sections. However, it should also be noted that as the number of signals per mile increases from one to four, the difference in accident rates drops from -26% to -3%.

It is also evident from Table 4.4 that the expected accident rates did not vary much. In fact, the accident rates were calculated from regression equations which were dependent only on the number of signals per mile.

Table 4.5 shows the expected total accident rates for six lane sections. As can be seen, accident rates for TWLTL and raised medians did not depend on the same variables. In an effort to provide a common basis for comparison, Table 4.6 was created. Table 4.6 is similar to Table 4.5 in all regards, except that raised median accidents were modeled as varying with the same variables as TWLTL already did. This model was not used originally because the additional variables do not explain enough information to be statistically significant.

Table 4.4: **Total Accidents/MVM Expected: 4 Lane Sections**

Signals per mile	Drives per mile	Approach per mile	ADT = 10,000 TWLTL	ADT = 10,000 RM	ADT = 30,000 TWLTL	ADT = 30,000 RM	ADT = 50,000 TWLTL	ADT = 50,000 RM
1	25	2	6.31	4.64	6.31	4.64	6.31	4.64
		4	6.31	4.64	6.31	4.64	6.31	4.64
		6	6.31	4.64	6.31	4.64	6.31	4.64
		8	6.31	4.64	6.31	4.64	6.31	4.64
	50	2	6.31	4.64	6.31	4.64	6.31	4.64
		4	6.31	4.64	6.31	4.64	6.31	4.64
		6	6.31	4.64	6.31	4.64	6.31	4.64
		8	6.31	4.64	6.31	4.64	6.31	4.64
2	25	2	8.60	7.36	8.60	7.36	8.60	7.36
		4	8.60	7.36	8.60	7.36	8.60	7.36
		6	8.60	7.36	8.60	7.36	8.60	7.36
		8	8.60	7.36	8.60	7.36	8.60	7.36
	50	2	8.60	7.36	8.60	7.36	8.60	7.36
		4	8.60	7.36	8.60	7.36	8.60	7.36
		6	8.60	7.36	8.60	7.36	8.60	7.36
		8	8.60	7.36	8.60	7.36	8.60	7.36
3	25	2	10.89	10.08	10.89	10.08	10.89	10.08
		4	10.89	10.08	10.89	10.08	10.89	10.08
		6	10.89	10.08	10.89	10.08	10.89	10.08
		8	10.89	10.08	10.89	10.08	10.89	10.08
	50	2	10.89	10.08	10.89	10.08	10.89	10.08
		4	10.89	10.08	10.89	10.08	10.89	10.08
		6	10.89	10.08	10.89	10.08	10.89	10.08
		8	10.89	10.08	10.89	10.08	10.89	10.08
4	25	2	13.18	12.80	13.18	12.80	13.18	12.80
		4	13.18	12.80	13.18	12.80	13.18	12.80
		6	13.18	12.80	13.18	12.80	13.18	12.80
		8	13.18	12.80	13.18	12.80	13.18	12.80
	50	2	13.18	12.80	13.18	12.80	13.18	12.80
		4	13.18	12.80	13.18	12.80	13.18	12.80
		6	13.18	12.80	13.18	12.80	13.18	12.80
		8	13.18	12.80	13.18	12.80	13.18	12.80

Table 4.5: Total Accidents/MVM Expected: 6 Lane Sections

Signals per mi	Drives per mile	Approach per mile	ADT = 20,000 TWLTL	ADT = 20,000 RM	ADT = 30,000 TWLTL	ADT = 30,000 RM	ADT = 40,000 TWLTL	ADT = 40,000 RM	ADT = 50,000 TWLTL	ADT = 50,000 RM
1	30	2	8.94	5.82	8.94	5.82	8.94	5.82	8.94	5.82
		4	9.83	5.82	9.83	5.82	9.83	5.82	9.83	5.82
		6	10.73	5.82	10.73	5.82	10.73	5.82	10.73	5.82
	60	2	6.36	5.82	6.36	5.82	6.36	5.82	6.36	5.82
		4	7.26	5.82	7.26	5.82	7.26	5.82	7.26	5.82
		6	8.15	5.82	8.15	5.82	8.15	5.82	8.15	5.82
2	30	2	12.02	7.78	12.02	7.78	12.02	7.78	12.02	7.78
		4	12.92	7.78	12.92	7.78	12.92	7.78	12.92	7.78
		6	13.82	7.78	13.82	7.78	13.82	7.78	13.82	7.78
	60	2	9.45	7.78	9.45	7.78	9.45	7.78	9.45	7.78
		4	10.34	7.78	10.34	7.78	10.34	7.78	10.34	7.78
		6	11.24	7.78	11.24	7.78	11.24	7.78	11.24	7.78
3	30	2	15.11	9.74	15.11	9.74	15.11	9.74	15.11	9.74
		4	16.01	9.74	16.01	9.74	16.01	9.74	16.01	9.74
		6	16.90	9.74	16.90	9.74	16.90	9.74	16.90	9.74
	60	2	12.53	9.74	12.53	9.74	12.53	9.74	12.53	9.74
		4	13.43	9.74	13.43	9.74	13.43	9.74	13.43	9.74
		6	14.33	9.74	14.33	9.74	14.33	9.74	14.33	9.74

Table 4.6: Total Accidents/MVM Expected using same variables: 6 Lane Sections

Signals per mi	Drives per mile	Approach per mile	ADT = 20,000 TWLTL	ADT = 20,000 RM	ADT = 30,000 TWLTL	ADT = 30,000 RM	ADT = 40,000 TWLTL	ADT = 40,000 RM	ADT = 50,000 TWLTL	ADT = 50,000 RM
1	30	2	8.94	5.34	8.94	5.34	8.94	5.34	8.94	5.34
		4	9.83	5.77	9.83	5.77	9.83	5.77	9.83	5.77
		6	10.73	6.20	10.73	6.20	10.73	6.20	10.73	6.20
	60	2	6.36	5.36	6.36	5.36	6.36	5.36	6.36	5.36
		4	7.26	5.78	7.26	5.78	7.26	5.78	7.26	5.78
		6	8.15	6.21	8.15	6.21	8.15	6.21	8.15	6.21
2	30	2	12.02	7.15	12.02	7.15	12.02	7.15	12.02	7.15
		4	12.92	7.58	12.92	7.58	12.92	7.58	12.92	7.58
		6	13.82	8.00	13.82	8.00	13.82	8.00	13.82	8.00
	60	2	9.45	7.16	9.45	7.16	9.45	7.16	9.45	7.16
		4	10.34	7.59	10.34	7.59	10.34	7.59	10.34	7.59
		6	11.24	8.02	11.24	8.02	11.24	8.02	11.24	8.02
3	30	2	15.11	8.95	15.11	8.95	15.11	8.95	15.11	8.95
		4	16.01	9.38	16.01	9.38	16.01	9.38	16.01	9.38
		6	16.90	9.81	16.90	9.81	16.90	9.81	16.90	9.81
	60	2	12.53	8.97	12.53	8.97	12.53	8.97	12.53	8.97
		4	13.43	9.40	13.43	9.40	13.43	9.40	13.43	9.40
		6	14.33	9.82	14.33	9.82	14.33	9.82	14.33	9.82

In regard to six lane section total accidents, the expected-value tables indicate that raised medians are safer for all ADT levels except when there are two or fewer signals per mile, there are four or fewer approaches per mile, and the number of driveways per mile exceeds 75 or when there are three signals per mile, at least 85 driveways per mile, 2 or fewer approaches per mile and the ADT is lower than 25,000.

These results should be viewed in light of the aforementioned independent variable combinations which were not covered by study data. Specifically, rates for the conditions where TWLTL were found to be safer represent an extrapolation from variable combinations present in the study sections. Of course, the same holds true for many of the conditions for which raised medians were found to be safer.

For four lane total accidents per MVM, raised medians were found to be safer for all conditions.

It is worth noting that these tables correspond well with the rate comparison shown earlier in this section (Table 4.1). Expected-value tables for sections and accident types show diversity in the type of median which is safer at a given variable level. For example, the expected-value table for four-lane section total accidents per mile per year, shown in Appendix F, shows raised medians to be safer for most conditions. However, TWLTL are safer for other conditions. This corresponds to a somewhat high alpha-error of 0.098 shown in the rate comparison (Table 4.1).

Chapter 5:
Comparison with Past Research

This section is intended to give the reader a basis for comparison of the results of this study. While no exhaustive results have been given, limited guidelines have been provided on the basis of the expected-value tables for total accidents per MVM.

Martin Parker's Virginia study (3) presented expected-value tables and a set of general guidelines. These were all developed from a study of four lane roads. The expected-value tables in that report indicate that with ADTs from 10,000 to 30,000, TWLTL have a lower number of accidents per mile when there are fewer than 30 driveways per mile and fewer than 5 streets per mile. In comparison, the expected-value table in Appendix F of this report shows that for four lane total accidents per mile per year a different relationship exists. Drives per mile was not found to be significant for either median type. Further, ADT is quite significant. At an ADT of 10,000, TWLTL are safer except when the approaches per mile are low. At an ADT of 30,000, raised medians are safer except with seven or more approaches per mile and two or fewer signals per mile. The relative safety of TWLTL under conditions of low signals per mile and a high number of approaches is probably attributable to the characteristics associated with less developed areas. Under such conditions, there are probably few points of concentrated left-turns. Such points seem to adversely affect TWLTL safety. The correspondence between ADT and accidents per mile per year is to be expected. As opposing traffic increases, left turns should become safer at concentrated and controlled points such as are found with raised medians.

Also, Parker's general guidelines were found to be applicable to the sections studied in this project only when considering accidents per mile per year. Parker recommends TWLTL when there are fewer than 12 streets per mile and the number of driveways per mile exceeds 50. While this project agrees with these guidelines based on the number of accidents per mile per year, on the basis of accidents per MVM, a TWLTL median would not be recommended for a four lane road.

Douglas Harwood (4), within subjective guidelines, such as the need to accommodate pedestrians, suggested that TWLTL should be used instead of raised medians when the number of driveways per mile exceeded 45 and there were low to moderate volumes of through traffic. Some of the expected-value tables developed in this report suggested the same thing. Certainly, driveways per mile should be high. Forty-five driveways per mile is a lower minimum than any of this report's tables would suggest. Although accidents per MVM remained constant with changing ADTs, accidents per mile per year preclude the use of TWLTL at higher ADT levels.

Joaquin Vargas' study (1) was based on a combination of four and six lane roadway sections. Vargas recommended raised medians with two or fewer signals per mile, more than 80 driveways per mile and less than 3000 peak hour volume (PHV). He found TWLTL to be safer for two to six signals per mile when there were fewer than 80 driveways per mile or when signals per mile exceeded six. The present study is not suitable for comparison above four signals per mile because of limitations in data obtained. However, for ranges that can be compared, the results of the present study run contrary to those in Vargas' report. The present study indicates that for TWLTL to be safer, a lower number of signals per mile is required. Also, TWLTL should have a high number of driveways per mile rather than less than 80 driveways per mile as his report suggests. One point of agreement occurs at the point of effect of ADT (or PHV as Vargas used). Higher ADT values favor raised medians.

The relative safety of TWLTL and raised medians may be inferred from Glennon's report(2). As discussed earlier, the application of Glennon's work is based on anticipated accident reduction from a previously undivided roadway. The accident-rate reductions were determined for a four-lane highway. From the comparison of expected accident reductions for each median type, for all ADT ranges, TWLTL were expected to be safer when "land development" was low to moderate. Low to moderate land development was used to describe areas with several concentrated sources of traffic and few low-volume driveways. The implication of Glennon's report is that for high-development areas, which are assumed to have no high-volume driveways and a large number of low-volume driveways, raised medians are safer. Further, when more high-volume driveways and fewer low-volume driveways are present, TWLTL would be safer. This is contrary to the results obtained in the present study as well as in other studies (3) (4). The unusual results obtained from Glennon's report most likely mean that the relative safety of median types can not be inferred from the accident reduction rates of those median types.

Chapter 6:
Conclusions

This study provides a comparison of accident rates between raised medians and two-way left-turn lanes (TWLTL). Regression equations have also been developed to model accident occurrence for each median type. As many sections as possible were used to lend accuracy to the study. In all, 48 TWLTL and 32 raised median sections were used. This has lent stability to the analysis performed.

Comparisons were made for total and midblock accidents, four and six lane sections, accidents per million vehicle miles (MVM) and accidents per mile per year, and injury, and all accidents occurring. While the comparisons of all of these combinations are interesting, total accidents per MVM is considered to give the best indication of the safety of a median type. The comparison of accidents occurring on six lane sections showed, with a low statistical error, raised medians to be safer than TWLTL. The accident comparison for four lane sections also showed raised medians to be safer, but with a higher statistical error.

The relative safety of raised medians probably resulted from the range of ADTs used. With higher volumes of opposing traffic, left-turns seem to be safer at concentrated points, such as raised medians provide. When turns are concentrated at certain points, the area in which conflicts occur is greatly reduced. The turns may also be better accommodated at concentrated points, using traffic signals, for example.

Regression equations were developed for sixteen conditions: Raised medians and TWLTL, four and six lane sections, total and midblock accidents, and accidents per mile per year and accidents per MVM. Again, for the purposes of accurately reflecting safety, total accidents per MVM should be used. The regression equations developed for the four section types using total accidents per MVM are listed on the following page.

TWLTL 6 Lane
$$Acc/MVM = 3.0871*SIG - 0.0859*DR + 0.4483*APP + 7.5315$$

TWLTL 4 Lane
$$Acc/MVM = 2.2913*SIG + 4.0178$$

Raised Median 6 Lane
$$Acc/MVM = 1.9620*SIG + 3.8556$$

Raised Median 4 Lane
$$Acc/MVM = 2.7209*SIG + 1.9184$$

Where: Acc/MVM = Total accidents per million vehicle miles
SIG = Signals per mile
DR = Driveways per mile
APP = Approaches per mile

For all of the regression models created, tables showing the expected accident rates were generated. The expected-value tables for the regression equations listed above produced results comparable to the accident rate comparison performed earlier.

It was found that, for four-lane sections, raised medians were always safer than TWLTL. However, it was also noted that the difference in rates was found to decrease with increasing numbers of signals per mile. For six lane sections, raised medians were again found to be safer except under certain conditions. TWLTL were safer when the following conditions were all met: High numbers of driveways per mile (at least 75), low numbers of signals per mile (two or fewer), and low numbers of approaches per mile (a maximum of five or six depending on signals per mile).

Results of this study compared fairly well with those of other research when viewed using the parameters of the other studies. This usually meant using four lane sections and accidents per mile per year for the comparison. The general guidelines developed in other research appear to be applicable, especially to six lane sections studied. For TWLTL to be safer than raised medians, traffic should be low with few concentrated sources of traffic entering or leaving the road.

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APPENDIX A:

SITE LOCATIONS

The following is an extended site description. Mileage references are made to the Georgia D.O.T. road inventories.

T1, T2, T3: SR 3 in Cobb County from mile 1.92 to mile 9.29. Cobb Parkway runs in and out of the city limits of Marietta with 4 through lanes. SR 3 was divided into 3 sites, and subsequently 5 sections, because of inconsistencies in geometrics. Specifically, the sites are separated by sections of raised medians.

T4: SR 9 in Fulton County from mile 19.38 to mile 20.69. Atlanta Street: in the city of Roswell having 4 through lanes.

T5: SR 9 in Fulton County from mile 6.41 to mile 17.61. Roswell Road: 4 lane section partially within the city limits of Atlanta.

T6: SR 54 in Clayton County from mile 8.22 to mile 13.49. Jonesboro Road: 4 lane section through the city limits of Morrow, Lake City, and Forest Park.

T7: SR 3 in Clayton County from mile 11.69 to mile 14.42. Old Dixie Road: 4 lane section through the city limits of Forest Park.

T8: SR 85 in Clayton County from mile 3.44 to mile 4.64. 4 lane section located in the city of Riverdale.

T9: SR 279 in Fulton County from mile 0.24 to mile 5.01. Old National Highway: 4 lane section.

T10: SR 155 in Dekalb County from mile 7.70 to mile 11.28. Candler Road: 4 lane section partially within the city limits of Atlanta.

T11: SR 10 in Dekalb County from mile 5.67 to mile 9.86. Memorial Drive: 6 lane section.

T12: SR 10 in Gwinnett County from mile 0.56 to mile 12.90. Snellville-Loganville Road: 4 lane section through Snellville city limits.

T13: SR 13 in Dekalb County from mile 0.00 to mile 6.75. Buford Highway: 6 lane section through Chamblee city limits and into Doraville city limits.

T14: SR 13 in Dekalb and Gwinnett Counties from mile 7.74 (Dekalb) to mile 2.35 (Gwinnett). Buford Highway: 4 lane section.

T15: SR 42 in Fulton County from mile 3.60 to mile 4.96. Moreland Avenue: 4 lane section. Site is located along the line between Dekalb and Fulton Counties. Accident data is coded for Fulton county while road inventory information is listed for Dekalb county.

T19: SR 52 in Whitfield County from mile 0.19 to mile 1.86. Walnut Avenue: 4 lane section.

R1: SR 140 in Fulton County from mile 6.82 to mile 8.24. Holcomb Bridge Road: 6 lane section in the city of Roswell.

R2: SR 331 in Clayton County from mile 1.23 to mile 3.31. Forest Parkway: 4 lane section in the city of Forest Park.

R3: SR 42 in Dekalb County from mile 0.70 to mile 3.55. Moreland Avenue: 6 lane section.

R4: SR 11 in Bibb County from mile 14.96 to mile 16.87. 4 lane section in the city of Macon.

R5: SR 22 in Bibb County from mile 11.69 to mile 13.47. 4 lane section in the city of Macon.

R6: SR 204 in Chatham County from mile 15.75 to mile 21.47. Abercorn Street: 6 lane section in the city of Savannah.

R7: SR 204 in Chatham County from mile 21.47 to mile 23.21. Abercorn Street: 4 lane section in the city of Savannah.

R8: SR 21 in Chatham County from mile 11.43 to mile 13.04. 4 lane section in the city of Savannah.

R9: SR 26 in Chatham County from mile 18.34 to mile 21.74. Victory Drive: 4 lane section in the city of Savannah.

R10 T16: SR 26 in Bulloch County from mile 17.86 to mile 18.99 and from mile 19.06 to mile 20.30, respectively. Both are 4 lane sections within the city limits of Statesboro.

R11: SR 4 in Richmond County from mile 16.96 to mile 20.73. 6 lane section in the city of Augusta. Also designated as US 1.

R12 T17: SR 121 in Richmond County from mile 10.12 to mile 13.26 and from mile 13.54 to mile 14.98, respectively. Peach Orchard Road: 6 lane sections in the city of Augusta.

R13 T18: SR 28 in Richmond County from mile 3.82 to mile 4.67 and from mile 7.32 to mile 10.76, respectively. Washington Road: 4 lane sections in the city of Augusta.

R14: SR 52 in Whitfield County from mile 2.52 to mile 4.32. Walnut Avenue: 6 lane section partially within the city limits of Dalton.

R15: SR 85 in Muscogee County from mile 3.43 to mile 4.82. 4 lane section in the city of Columbus.

R16: SR 1 in Muscogee County from mile 2.68 to mile 6.70. 6 lane section in the city of Columbus. Also designated as US 27 and US 280.

R17 R18: SR 1 in Muscogee County from mile 6.70 to mile 11.06, excluding a 1.20 mile section. 4 lane sections in the city of Columbus.

R19 T20: SR 141 in Dekalb County from 5.37 to mile 7.23 and from 2.26 to mile 4.88. Peachtree Industrial Boulevard: 4 lane sections through the city limits of Chamblee and Doraville.

APPENDIX B:

ACCIDENT RATES BY SECTION

Raised Median Compilation: Total Accidents: Four Lane Sections

Site	Acc/mi per year	Acc per MVM	Injury Acc /mi/yr	Injury Acc/MVM	Fatal Acc /mi/yr	Fatal Acc/MVM
R2A	43.85	4.79	10.51	1.15	0.26	0.03
R2B	26.07	3.93	7.26	1.10	0.00	0.00
R4	19.20	2.75	5.06	0.72	0.35	0.05
R5	74.53	8.33	18.54	2.07	0.37	0.04
R7	65.90	8.53	21.46	2.78	0.00	0.00
R8	23.40	3.30	5.59	0.79	0.21	0.03
R9	113.04	12.96	25.69	2.95	0.29	0.03
R10	20.06	5.40	4.13	1.11	0.00	0.00
R13	147.09	26.78	29.07	5.29	0.58	0.11
R15	122.30	12.49	18.71	1.91	0.48	0.05
R17	43.22	4.88	11.33	1.28	0.11	0.01
R18A	57.58	5.31	8.71	0.80	0.38	0.03
R18B	69.79	6.52	16.67	1.56	0.52	0.05
R18C	78.03	9.18	13.45	1.58	0.38	0.04
R19	129.39	6.00	27.42	1.27	0.54	0.02
Means	70.91	7.67	15.76	1.70	0.29	0.03
Std Dev	42.15	6.01	8.36	1.19	0.20	0.03

Raised Median Compilation: Total Accidents: Six Lane Sections

Site	Acc/mi per year	Acc per MVM	Injury Acc /mi/yr	Injury Acc/MVM	Fatal Acc /mi/yr	Fatal Acc/MVM
R1	141.55	9.31	30.52	2.01	0.00	0.00
R3A	49.80	4.83	13.25	1.29	0.80	0.08
R3B	27.72	2.67	7.26	0.70	0.50	0.05
R6A	59.93	7.37	14.14	1.74	0.34	0.04
R6B	65.19	4.83	15.63	1.16	0.59	0.04
R6C	152.58	9.38	41.47	2.55	0.60	0.04
R6D	262.07	15.22	49.04	2.85	0.00	0.00
R6E	153.97	10.26	31.11	2.07	0.00	0.00
R11A	79.40	6.84	18.98	1.64	0.23	0.02
R11B	139.37	12.50	33.97	3.05	0.95	0.09
R11C	163.02	18.61	39.32	4.49	0.52	0.06
R12A	37.37	5.03	11.11	1.50	0.25	0.03
R12B	83.99	8.67	16.83	1.74	0.66	0.07
R14	55.93	5.94	11.85	1.26	0.19	0.02
R16A	82.05	7.93	18.72	1.81	0.51	0.05
R16B	95.73	7.25	23.73	1.80	0.27	0.02
R16C	43.08	3.95	12.47	1.14	0.23	0.02
Means	94.07	8.15	21.87	1.90	0.39	0.03
Std Dev	61.17	4.13	12.38	0.90	0.28	0.03

TWLTL Total Accidents: Four Lane Sections

Site	Acc/mi per year	Accidents per MVM	Injury Acc /mi /year	Injury Acc per MVM	Fatal Acc /mi /year	Fatal Acc per MVM
T1A	410.87	24.71	104.59	6.29	0.48	0.03
T1B	146.63	9.93	40.46	2.74	0.00	0.00
T1C	169.38	11.12	47.85	3.14	0.16	0.01
T2	171.43	12.38	34.69	2.51	0.00	0.00
T3	62.96	5.44	12.54	1.08	0.00	0.00
T4	80.15	6.35	18.58	1.47	0.25	0.02
T5A	126.70	10.60	27.42	2.29	0.14	0.01
T5B	121.32	8.65	26.94	1.92	0.39	0.03
T5C	286.27	19.39	43.92	2.98	0.39	0.03
T5D	238.46	18.28	46.15	3.54	0.00	0.00
T5E	67.09	6.05	17.09	1.54	0.43	0.04
T5F	56.58	5.10	13.45	1.21	0.00	0.00
T5G	94.37	7.35	22.07	1.72	0.30	0.02
T6A	103.98	13.86	18.87	2.51	0.00	0.00
T6B	34.50	4.14	8.19	0.98	0.00	0.00
T6C	139.78	12.46	29.78	2.65	0.00	0.00
T6D	95.51	10.88	23.40	2.67	0.00	0.00
T7	84.37	10.77	18.56	2.37	0.24	0.03
T8	216.94	16.53	46.11	3.51	0.00	0.00
T9A	20.72	5.49	9.91	2.63	0.45	0.12
T9B	22.78	4.01	6.67	1.17	0.00	0.00
T9C	45.72	4.47	13.57	1.33	0.00	0.00
T9D	143.03	8.64	36.67	2.21	0.00	0.00
T10A	161.95	18.67	36.36	4.19	0.00	0.00
T10B	93.75	11.93	25.35	3.23	0.00	0.00
T10C	107.57	13.67	23.93	3.04	0.00	0.00
T12A	78.54	5.40	17.24	1.18	0.19	0.01
T12B	58.73	4.40	12.17	0.91	0.53	0.04
T12C	44.72	2.35	11.55	0.61	0.17	0.01
T12D	83.75	6.14	20.17	1.48	0.28	0.02
T12E	33.33	3.20	7.32	0.70	0.00	0.00
T12F	24.54	2.42	7.69	0.76	0.73	0.07
T12G	6.67	1.23	2.60	0.48	0.00	0.00
T12H	3.40	0.98	1.13	0.33	0.00	0.00

(continued on next page)

Site	Acc/mi per year	Accidents per MVM	Injury Acc /mi /year	Injury Acc per MVM	Fatal Acc /mi /year	Fatal Acc per MVM
T14	109.11	12.38	22.49	2.55	0.00	0.00
T15	46.57	5.67	12.50	1.52	0.00	0.00
T16	23.92	4.57	4.84	0.92	0.00	0.00
T18A	147.21	10.13	23.72	1.63	0.23	0.02
T18B	156.59	11.42	25.58	1.87	0.78	0.06
T19	47.70	4.22	7.98	0.71	0.00	0.00
T20A	65.80	5.43	11.76	0.97	0.22	0.02
T20B	129.05	9.71	21.10	1.59	0.00	0.00
Means	99.45	8.99	22.14	2.00	0.14	0.01
Std Dev	79.83	5.37	17.93	1.18	0.21	0.02

TWLTL Total Accidents: Six Lane Sections

Site	Acc/mi per year	Accidents per MVM	Injury Acc /mi /year	Injury Acc per MVM	Fatal Acc /mi /year	Fatal Acc per MVM
T11A	236.55	13.59	145.45	8.36	0.76	0.04
T11B	146.67	10.07	31.31	2.15	0.20	0.01
T11C	73.93	7.16	15.81	1.53	0.00	0.00
T13A	106.98	9.98	29.13	2.72	0.44	0.04
T13B	144.86	14.54	34.16	3.43	0.82	0.08
T13C	81.28	8.19	17.83	1.80	0.18	0.02
T13D	173.27	12.27	40.88	2.89	0.00	0.00
T17	84.49	9.76	18.06	2.09	0.46	0.05
Means	130.26	10.82	43.46	3.61	0.38	0.03
Std Dev	55.85	2.57	42.91	2.20	0.32	0.03

Raised Median Compilation: Midblock Accidents: Four Lane Sections

Site	Acc/mi per year	Acc per MVM	Injury Acc /mi/yr	Injury Acc/MVM	Fatal Acc /mi/yr	Fatal Acc/MVM
R2A	5.38	0.59	0.51	0.06	0.00	0.00
R2B	5.13	0.77	1.28	0.19	0.00	0.00
R4	5.41	0.77	1.40	0.20	0.35	0.05
R5	19.66	2.20	5.24	0.59	0.00	0.00
R7	2.68	0.35	0.96	0.12	0.00	0.00
R8	6.83	0.96	1.66	0.23	0.00	0.00
R9	17.25	1.98	4.90	0.56	0.10	0.01
R10	1.47	0.40	0.29	0.08	0.00	0.00
R13	22.09	4.02	1.74	0.32	0.00	0.00
R15	12.95	1.32	2.16	0.22	0.00	0.00
R17	1.44	0.16	0.22	0.03	0.11	0.01
R18A	8.71	0.80	2.65	0.24	0.38	0.03
R18B	5.21	0.49	2.34	0.22	0.00	0.00
R18C	7.77	0.91	1.89	0.22	0.00	0.00
R19	55.91	2.59	12.54	0.58	0.18	0.01
Totals						
Means	12.39	1.34	2.92	0.32	0.08	0.01
Std Dev	13.79	1.05	3.10	0.18	0.13	0.02

Raised Median Compilation: Midblock Accidents: Six Lane Sections

Site	Acc/mi per year	Acc per MVM	Injury Acc /mi/yr	Injury Acc/MVM	Fatal Acc /mi/yr	Fatal Acc/MVM
R1	60.56	3.98	10.80	0.71	0.00	0.00
R3A	18.47	1.79	4.42	0.43	0.80	0.08
R3B	9.74	0.94	2.31	0.22	0.33	0.03
R6A	11.78	1.45	2.36	0.29	0.00	0.00
R6B	12.68	0.94	3.83	0.28	0.00	0.00
R6C	32.94	2.02	8.53	0.52	0.20	0.01
R6D	37.55	2.18	8.05	0.47	0.00	0.00
R6E	24.44	1.63	6.03	0.40	0.00	0.00
R11A	30.32	2.61	7.41	0.64	0.00	0.00
R11B	38.73	3.47	6.98	0.63	0.00	0.00
R11C	37.50	4.28	8.85	1.01	0.26	0.03
R12A	9.85	1.33	2.27	0.31	0.25	0.03
R12B	17.16	1.77	2.64	0.27	0.00	0.00
R14	13.52	1.44	2.78	0.29	0.00	0.00
R16A	10.26	0.99	2.56	0.25	0.00	0.00
R16B	12.80	0.97	4.27	0.32	0.00	0.00
R16C	8.84	0.81	2.49	0.23	0.00	0.00
Means	22.13	1.92	4.93	0.43	0.10	0.01
Std Dev	14.63	1.08	2.82	0.21	0.21	0.02

TWLTL Midblock Accidents: Four Lane Sections

Site	Acc/mi per year	Accidents per MVM	Injury Acc /mi /year	Injury Acc/MVM	Fatal Acc /mi /year	Fatal Acc/MVM
T1A	259.18	15.59	70.05	4.21	0.48	0.03
T1B	77.26	5.23	23.70	1.61	0.00	0.00
T1C	84.37	5.54	22.97	1.51	0.16	0.01
T2	36.05	2.60	8.84	0.64	0.00	0.00
T3	16.24	1.40	4.84	0.42	0.00	0.00
T4	32.06	2.54	6.87	0.54	0.00	0.00
T5A	35.06	2.93	8.66	0.72	0.00	0.00
T5B	43.99	3.14	8.72	0.62	0.19	0.01
T5C	92.55	6.27	10.20	0.69	0.00	0.00
T5D	95.60	7.33	16.12	1.24	0.00	0.00
T5E	51.71	4.66	13.68	1.23	0.43	0.04
T5F	29.41	2.65	7.28	0.66	0.00	0.00
T5G	41.33	3.22	10.81	0.84	0.15	0.01
T6A	51.15	6.82	9.64	1.29	0.00	0.00
T6B	9.94	1.19	2.92	0.35	0.00	0.00
T6C	31.33	2.79	6.89	0.61	0.00	0.00
T6D	31.73	3.61	7.05	0.80	0.00	0.00
T7	25.52	3.26	5.86	0.75	0.12	0.02
T8	77.78	5.93	15.00	1.14	0.00	0.00
T9A	5.86	1.55	2.70	0.72	0.45	0.12
T9B	5.56	0.98	1.48	0.26	0.00	0.00
T9C	20.94	2.05	6.78	0.66	0.00	0.00
T9D	66.97	4.04	17.88	1.08	0.00	0.00
T10A	40.40	4.66	11.11	1.28	0.00	0.00
T10B	52.43	6.67	12.50	1.59	0.00	0.00
T10C	22.49	2.86	4.91	0.62	0.00	0.00
T12A	40.04	2.75	8.43	0.58	0.19	0.01
T12B	19.58	1.47	5.82	0.44	0.00	0.00
T12C	11.39	0.60	2.64	0.14	0.00	0.00
T12D	20.73	1.52	6.44	0.47	0.28	0.02
T12E	15.85	1.52	3.66	0.35	0.00	0.00
T12F	7.33	0.72	2.56	0.25	0.37	0.04
T12G	2.76	0.51	0.81	0.15	0.00	0.00
T12H	2.13	0.61	0.71	0.20	0.00	0.00

	Acc/mi per year	Accidents per MVM	Injury Acc /mi /year	Injury Acc/MVM	Fatal Acc /mi /year	Fatal Acc/MVM
T14	25.49	2.89	5.65	0.64	0.00	0.00
T15	13.97	1.70	2.70	0.33	0.00	0.00
T16	5.38	1.03	0.81	0.15	0.00	0.00
T18A	61.86	4.26	9.77	0.67	0.00	0.00
T18B	68.99	5.03	9.30	0.68	0.00	0.00
T19	21.36	1.89	2.00	0.18	0.00	0.00
T20A	14.38	1.19	2.40	0.20	0.00	0.00
T20B	23.24	1.75	3.36	0.25	0.00	0.00
Means	38.78	3.50	8.91	0.81	0.06	0.01
Std Dev	42.96	2.70	11.10	0.68	0.14	0.02

TWLTL Midblock Accidents: Six Lane Sections

Site	Acc/mi per year	Accidents per MVM	Injury Acc /mi /year	Injury Acc/MVM	Fatal Acc /mi /year	Fatal Acc/MVM
T11A	118.37	6.80	29.17	1.68	0.76	0.04
T11B	57.78	3.97	13.33	0.92	0.20	0.01
T11C	29.91	2.90	4.70	0.46	0.00	0.00
T13A	41.75	3.89	11.96	1.12	0.22	0.02
T13B	42.80	4.30	14.40	1.45	0.82	0.08
T13C	23.35	2.35	8.56	0.86	0.18	0.02
T13D	53.46	3.78	12.26	0.87	0.00	0.00
T17	25.69	2.97	6.25	0.72	0.23	0.03
Means	50.46	4.19	13.14	1.09	0.30	0.02
Std Dev	30.63	1.35	7.54	0.39	0.32	0.03

APPENDIX C:

SECTION CHARACTERISTICS

Raised Median Site Data: 4 Lane Sections

Site	Distance	ADT	Drives per mile	Signals per mile	Apprch per mile	Opening per mile
R2A	1.30	25090	46.92	3.08	4.62	3.08
R2B	0.78	18150	37.18	2.56	8.97	3.85
R4	1.91	19155	10.47	0.00	5.24	2.09
R5	1.78	24525	33.71	2.81	3.37	4.49
R7	1.74	21162	42.53	2.30	24.14	13.79
R8	1.61	19417	13.04	0.00	4.35	3.11
R9	3.40	23888	23.53	2.35	5.29	2.94
R10	1.13	10180	35.40	0.88	12.39	9.73
R13	0.86	15048	76.74	8.14	1.16	2.33
R15	1.39	26825	64.75	3.60	9.35	4.32
R17	3.00	24265	5.00	0.33	4.67	2.00
R18A	0.88	29684	28.41	1.14	4.55	2.27
R18B	1.28	29325	31.25	2.34	4.69	2.34
R18C	1.76	23286	37.50	2.27	5.68	1.14
R19	1.86	59070	19.89	2.15	3.23	2.15
Totals	24.68					
Std Dev		10866	19.30	1.97	5.54	3.38

Raised Median Site Data: 6 Lane Sections

Site	Distance	ADT	Drives per mile	Signals per mile	Apprch per mile	Opening per mile
R1	1.42	41670	44.37	2.11	4.23	2.11
R3A	0.83	28247	28.92	2.41	3.61	3.61
R3B	2.02	28414	24.26	1.49	2.48	2.97
R6A	0.99	22290	18.18	2.02	2.02	3.03
R6B	1.13	36973	27.43	0.88	2.65	3.54
R6C	1.68	44570	30.95	1.79	4.17	1.79
R6D	0.87	47180	49.43	3.45	14.94	0.00
R6E	1.05	41120	34.29	4.76	4.76	0.00
R11A	1.44	31780	53.47	1.39	9.03	2.78
R11B	1.05	30550	67.62	2.86	3.81	2.86
R11C	1.28	24000	35.94	2.34	2.34	2.34
R12A	1.32	20360	22.73	1.52	3.03	3.03
R12B	2.02	26550	69.31	2.97	8.42	7.43
R14	1.80	25805	35.56	2.78	1.11	1.67
R16A	1.30	28350	60.00	3.08	8.46	6.92
R16B	1.25	36178	106.40	2.40	4.80	2.40
R16C	1.47	29862	66.67	0.00	6.80	2.72
Totals	22.92					
Std Dev		7969	22.84	1.08	3.48	1.91

TWLTL Site Data: 4 Lane Sections

Site	Distance	ADT	Drives per mile	Signal per mile	Apprch per mile
T1A	1.38	45560	52.17	2.90	0.72
T1B	1.73	40450	28.90	2.31	2.89
T1C	2.09	41740	60.77	1.44	0.96
T2	0.49	37940	40.82	2.04	8.16
T3	1.17	31724	46.15	0.85	3.42
T4	1.31	34608	83.21	1.53	9.16
T5A	2.31	32740	72.29	1.30	6.49
T5B	1.72	38440	52.91	2.33	6.40
T5C	0.85	40440	103.53	7.06	2.35
T5D	0.91	35730	86.81	4.40	2.20
T5E	0.78	30400	30.77	0.00	2.56
T5F	2.38	30400	10.08	0.00	0.84
T5G	2.25	35197	36.00	1.78	4.00
T6A	1.59	20560	42.77	2.52	3.77
T6B	1.14	22830	56.14	0.88	8.77
T6C	1.50	30737	40.67	3.33	5.33
T6D	1.04	24050	70.19	2.88	2.88
T7	2.73	21468	41.03	2.56	2.93
T8	1.20	35956	88.33	2.50	3.33
T9A	0.74	10340	16.22	2.70	2.70
T9B	1.80	15570	29.44	0.56	5.00
T9C	1.13	28000	50.44	0.88	5.31
T9D	1.10	45360	73.64	0.91	4.55
T10A	0.99	23770	44.44	3.03	4.04
T10B	0.96	21530	72.92	5.21	5.21
T10C	1.63	21562	81.60	4.29	6.75
T12A	1.74	39880	53.45	1.15	6.32
T12B	1.26	36570	39.68	0.79	3.97
T12C	2.02	52240	39.60	0.99	6.44
T12D	1.19	37400	65.55	3.36	5.88
T12E	0.82	28560	52.44	1.22	7.32
T12F	0.91	27780	29.67	0.00	5.49
T12G	2.05	14820	10.73	0.49	3.41
T12H	2.35	9500	20.85	0.00	3.83

Site	Distance	ADT	Drives per mile	Signal per mile	Apprch per mile
T14	2.89	24150	39.10	1.73	5.88
T15	1.36	22483	30.15	1.47	3.68
T16	1.24	14340	33.06	1.61	5.65
T18A	2.15	39828	68.84	2.33	1.40
T18B	1.29	37570	60.47	3.88	5.43
T19	1.67	30947	47.90	0.60	8.98
T20A	1.53	33190	40.52	4.58	1.96
T20B	1.09	36410	62.39	3.67	4.59
Totals	62.48				
Stand Dev		9881	21.67	1.56	2.19

TWLTL Site Data: 6 Lane Sections

Site	Distance	ADT	Drives per mile	Signal per mile	Apprch per mile
T11A	1.76	47685	67.61	3.41	1.70
T11B	1.65	39900	48.48	1.82	1.82
T11C	0.78	28300	61.54	1.28	2.56
T13A	3.01	29375	55.81	1.99	1.00
T13B	0.81	27300	60.49	3.70	2.47
T13C	1.87	27180	36.90	1.07	3.21
T13D	1.06	38700	144.34	5.66	0.00
T17	1.44	23712	95.14	2.08	8.33
Totals	12.38				
Stand Dev		8308.19	33.96	1.54	2.51

APPENDIX E:

GUIDE TO USING BMDP ON GEORGIA TECH'S CYBER

This appendix is intended to aid the reader in running BMDP software on the Georgia Tech Cyber B mainframe computer from a terminal cluster. It is assumed that the reader has an ID account number and password for the system. It is further assumed that the reader can log onto the system.

Logging onto Cyber may be accomplished from any terminal cluster on campus. Once a user is logged on, it is important to be sure that the account is operating in Batch mode. When in Batch mode, a "/" will always appear as a prompt on the screen. If this prompt does not appear, type "BATCH".

BMDP programs are stored by Cyber. In order to run a particular program, it must be attached to a user's local file. The BMDP program is attached from the computer library called CCLIB83. The program is then executed with a user-created instruction file and data file.

Files are created by typing "NEW, filename". It is a good idea to keep filenames as short and descriptive as possible. For example, a good name for the instruction file would be "INSTR". Once the file has been created, it is in the user's local workspace. In order to save a new file, type "SAVE, filename". To save an old file that has been altered, type "REPLACE, filename".

There are two editing programs on Cyber which may be used to change a file's contents. TED is a line editor. FSE is a full screen editor, which , to the experienced user, is easier to use. This appendix uses TED for the purpose of creating and changing an instruction file and a data file.

To create the data file to be used by BMDP:

-Type "NEW, filename"
-Type "TED, filename". The prompt will change to "0 ?"
-Hit the return key. The prompt will become "1I"
-Enter the data as numbers only--no commas, punctuation of any kind, or letters.
-Data is entered in a columnar format. Each line of text (numbers) will represent one site. Separate the information with at least one space. Columns represent data for each variable. It is important to be consistent

when entering data, every line must have data entered in the same order as every other line. The data file for three sites with four variables would look like:

#####	####	###	####
#####	####	###	####
#####	####	###	####

-No labels are required in this file. The instruction file is used to identify the data.
-Press return. The program will return to edit mode. The prompt will return to a "4 ?", for instance.

If data needs to be edited:

-To view the file, type "P 1 20" to print lines 1 through 20 of the file. This works for any range of lines.
-Move to the line in error by typing its number.
-To change an incorrect entry, type "C/mistake/correction/". The slash bars are delimeters. A period may be substituted for the slash bar if the item to be changed includes a slash bar.

Once the file is correct:

-Type "EXIT". The prompt "/" will appear, indicating that the user is back in local workspace.
-Save the file. ("SAVE, filename" or "REPLACE, filename")

The instruction file is created in a similar manner. A sample instruction file is reproduced below. This file is generic enough to be used in BMDP1R, BMDP2R, and BMDP9R programs. These are the three regression programs used to develop regression equations. When it is used, some of the terms will be ignored by the program. While such ignored terms generate warning messages, they do not affect the operation of the program.

The instruction file should be created by following the same procedures as used with the data file. In the example below, upper case letters and punctuation should be typed as they appear, lower case letters are names to be changed according to existing conditions. The # symbol indicates the number of variables (columns of data) that are present in the data file. Quotes, commas, and periods at the end of every line are crucial. This has proven to be a useful instruction file:

```
/PROBLEM    TITLE IS 'name of regression equation'.
/INPUT      FORMAT IS FREE.
            VARIABLES ARE #.
```

```
                FILE = data filename.
/VARIABLE       NAMES ARE var1, var2, var3, var4, varn.
/REGRESS        DEPENDENT IS dependent variable such as var2.
                INDEPENDENT ARE independent variables such as var1, var3, var4.
/PRINT          RREG.
                DATA.
                COVARIANCE.
                PARTIAL.
                FRATIO.
                CORRELATION.
/PLOT           VARIABLES, NAMES ARE var1, var3, var4.
                NORMAL.
                RESIDUALS.
/END
```

The instruction file should be saved in the same manner as the data file.

This instruction file names the variables found in the data file. Therefore, it is important to name the variables, in line 5, in the same sequence as they are found in the data file. Even if they are not to be used, all variables (columns of data) must be named. For the same reason, the number of variables must equal the number of columns used in establishing the data file.

When using this instruction file for BMDP1R, the variables specified as independent (line 7), must be limited to only those that are to be in the equation. For BMDP2R and BMDP9R, all independent variables should be listed initially. This allows the program to choose the best variable set.

Once both the data and instruction files have been created, BMDP may be run. The following command sequence will run BMDP9R. The other two regression programs may be run in the same manner.

-Move data and instruction files into local workspace by typing "GET, filename" for each file.
-Access to BMDP is obtained by typing "ATTACH, BMDP9R/UN=CCLIB83".
-To run the program, type "BMDP9R, I=instruction filename, L=output filename".
 For example, BMDP9R, I=INSTR, L=OR6TV9.
-Save the output file.
-To send the output file to the laser printer at the Rich Building, type "LINK, filename". To send the file to the Civil Engineering printer, type "LINK, filename, GTCE". During initial runs, a user should view a file on the

terminal screen before printing it in order to make sure the file ran correctly. Files can be viewed using TED or FSE.

The output format will vary among the three programs. All start with an echo of the instruction file. The programs also all present statistics about the data found in the data file. BMDP9R lists the regression equation under the heading "Statistics of 'best' subset". BMDP2R uses the title "Stepwise Regression Coefficients" and asterisks by indicated variables. As can be seen in the example output that follows, BMDP1R lists the equation following the correlation matrix.

A portion of an output file from BMDP1R is shown on the following pages. The first page of the report is an echo of the instruction file and is not shown here. The second page list the output parameters. At the bottom of the this page are the statistics for the data file used. Page three containing the covariance matrix for the data is also not shown. A correlation matrix of all of the data is shown on page four. The results of the analysis are located on page five. Statistics about the equation are first given. Then the equation coefficients are presented. Page six holds a correlation matrix of regression coefficients. A comparison of the predicted dependent variable with the actual value is listed on a case by case basis on page seven. Further pages hold graphs of residuals and others of predicted and observed values.

```
PROBLEM TITLE IS
RAISED MEDIAN 6 LANE TOTAL ACC/MVM

NUMBER OF VARIABLES TO READ IN. . . . . . . . .        7
NUMBER OF VARIABLES ADDED BY TRANSFORMATIONS. .        0
TOTAL NUMBER OF VARIABLES . . . . . . . . . . .        7
NUMBER OF CASES TO READ IN. . . . . . . . . . . TO END
CASE LABELING VARIABLES . . . . . . . . . . . .
MISSING VALUES CHECKED BEFORE OR AFTER TRANS. . NEITHER
BLANKS ARE. . . . . . . . . . . . . . . . . . . MISSING
INPUT FILE. . . . . . . . UNIT    7 . . . . . .DR6T
REWIND INPUT UNIT PRIOR TO READING. . DATA. . .    YES
NUMBER OF WORDS OF DYNAMIC STORAGE. . . . . . .   9998

VARIABLES TO BE USED
     1 ADT          2 ACCMIYR      3 ACCMVM       4 DRIVES       5 SIGNAL
     6 APPRCH       7 OPEN

INPUT FORMAT IS
FREE

MAXIMUM LENGTH DATA RECORD IS   80 CHARACTERS.

* * * WARNING * * * IN PARAGRAPH PRINT    THE FOLLOWING TEXT IS IGNORED:
PARTIAL. FRATIO.
* * * NOTE THAT THE FOLLOWING STATEMENTS WERE NOT FOUND:
LIN       LEV       NEW       VNAM      GNAM      VUS       VALU      PAGE
DEBU

THE MOST COMMON EXPLANATIONS FOR EXTRANEOUS CONTROL LANGUAGE ARE:
- MISSPELLED PARAGRAPH OR SENTENCE NAME
- SENTENCE IN THE WRONG PARAGRAPH
- SENTENCE OR PARAGRAPH REPEATED UNEXPECTEDLY
- OPTION NOT DEFINED IN THIS PROGRAM
- MUTUALLY EXCLUSIVE OPTIONS SELECTED

   REGRESSION INTERCEPT. . . . . . . . . . . . . . .NON-ZERO
   GROUPING VARIABLE . . . . . . . . . . . . . . . .
   WEIGHT VARIABLE . . . . . . . . . . . . . . . . .
   PRINT COVARIANCE MATRIX . . . . . . . . . . . . .     YES
   PRINT CORRELATION MATRIX. . . . . . . . . . . . .     YES
   PRINT CORRELATION OF REGRESSION COEFFICIENTS. .       YES
   PRINT RESIDUALS . . . . . . . . . . . . . . . . .     YES
   PRINT NORMAL PROBABILITY PLOT . . . . . . . . . .     YES
   PRINT DETRENDED NORMAL PROBABILITY PLOT . . . .       YES

 NUMBER OF CASES READ. . . . . . . . . . . . . . .     17
```

VARIABLE	MEAN	STANDARD DEVIATION	COEFFICIENT OF VARIATION	MINIMUM	MAXIMUM
1 ADT	31994.05882	7969.27493	.24909	20360.00000	47180.00000
2 ACCMIYR	99.57353	61.17413	.61436	27.72000	262.07000
3 ACCMVM	8.27000	4.13198	.49963	2.67000	18.61000
4 DRIVES	45.61941	22.84242	.50072	18.18000	106.40000
5 SIGNAL	2.25000	1.08196	.48087	.00000	4.76000
6 APPRCH	5.09765	3.47635	.68195	1.11000	14.94000
7 OPEN	2.89412	1.91106	.66032	.00000	7.43000

PAGE 4 BMDP1R RAISED MEDIAN 6 LANE TOTAL ACC/MVM

CORRELATION MATRIX

		ADT 1	ACCMIYR 2	ACCMVM 3	DRIVES 4	SIGNAL 5	APPRCH 6	OPEN 7
ADT	1	1.0000						
ACCMIYR	2	.6898	1.0000					
ACCMVM	3	.2656	.8584	1.0000				
DRIVES	4	.1625	.1420	.1203	1.0000			
SIGNAL	5	.2450	.5425	.5137	.0905	1.0000		
APPRCH	6	.4411	.5158	.2885	.4150	.2262	1.0000	
OPEN	7	-.5066	-.4847	-.2750	.2211	-.1443	.0481	1.000

PAGE 5 BMDP1R RAISED MEDIAN 6 LANE TOTAL ACC/MVM

REGRESSION TITLE IS
RAISED MEDIAN 6 LANE TOTAL ACC/MVM

DEPENDENT VARIABLE. . . . . 3 ACCMVM
TOLERANCE 0100
ALL DATA CONSIDERED AS A SINGLE GROUP

MULTIPLE R .5433 STD. ERROR OF EST. 3.8483
MULTIPLE R-SQUARE .2952

ANALYSIS OF VARIANCE

	SUM OF SQUARES	DF	MEAN SQUARE	F RATIO	P(TAIL)
REGRESSION	80.6473	3	26.8824	1.815	.1941
RESIDUAL	192.5245	13	14.8096		

VARIABLE		COEFFICIENT	STD. ERROR	STD. REG COEFF	T	P(2 TAIL)	TOLERANCE
INTERCEPT		3.09296					
DRIVES	4	.47911E-03	.46292E-01	.003	.010	.9919	.82779
SIGNAL	5	1.80513	.91287	.473	1.977	.0696	.94882
APPRCH	6	.21454	.31099	.180	.690	.5024	.79192

PAGE 6 BMDP1R RAISED MEDIAN 6 LANE TOTAL ACC/MVM

CORRELATION MATRIX OF REGRESSION COEFFICIENTS

		DRIVES 4	SIGNAL 5	APPRCH 6
DRIVES	4	1.0000		
SIGNAL	5	.0038	1.0000	
APPRCH	6	-.4067	-.2082	1.0000

PAGE 7 BMDP1R RAISED MEDIAN 6 LANE TOTAL ACC/MVM

LIST OF PREDICTED VALUES, RESIDUALS, AND VARIABLES
NOTE - NEGATIVE CASE NUMBER DENOTES A CASE WITH MISSING VALUES.
THE NUMBER OF STANDARD DEVIATIONS FROM THE MEAN IS DENOTED BY UP TO 3 ASTERISK
OF EACH RESIDUAL OR VARIABLE.
MISSING VALUES AND VALUES OUT OF RANGE ARE DENOTED BY VALUES
GREATER THAN OR EQUAL TO .2127E+38 IN ABSOLUTE VALUE.

CASE LABEL	NO.	RESIDUAL		PREDICTED VALUE	VARIABLES 1 ADT 7 OPEN	2 ACCMIYR		3 ACCMVM		4 DR
	1	1.479		7.831	.4167E+05* 2.110	141.6		9.310		44.37
	2	-3.402		8.232	.2825E+05 3.610	49.80		4.830		28.92
	3	-3.656		6.326	.2841E+05 2.970	27.72	*	2.670	*	24.26
	4	.1886		7.181	.2229E+05* 3.030	59.93		7.370		18.18
	5	-.4331		5.263	.3697E+05 3.540	65.19		4.830		27.43
	6	2.146		7.234	.4457E+05* 1.790	152.6		9.380		30.95
	7	2.670		12.55	.4718E+05* 0. *	262.1	**	15.22	*	49.43
	8	-2.463		12.72	.4112E+05* 0. *	154.0		10.26		34.29
	9	-.7250		7.565	.3178E+05 2.780	79.40		6.840		53.47
	10	3.395		9.105	.3055E+05 2.860	139.4		12.50	*	67.62
	11	10.77	**	7.836	.2400E+05* 2.340	163.0	*	18.61	**	35.94
	12	-1.468		6.498	.2036E+05* 3.030	37.37	*	5.030		22.73
	13	-1.624		10.29	.2655E+05 7.430 **	83.99		8.670		69.31
	14	-2.426		8.366	.2581E+05 1.670	55.93		5.940		35.56
	15	-2.567		10.50	.2835E+05 6.920 **	82.05		7.930		60.00
	16	-1.256		8.506	.3618E+05 2.400	95.73		7.250		106.4
	17	-.6338		4.584	.2986E+05 2.720	43.08		3.950	*	66.67

SERIAL CORRELATION OF RESIDUALS = .2171

APPENDIX F:

EXPECTED ACCIDENT RATE TABLES
(BASED ON REGRESSION EQUATIONS DEVELOPED)

Total Accidents/MVM Expected: 6 Lane Sections

Signals per mi	Drives per mile	Approach per mile	ADT = 20,000 TWLTL	ADT = 20,000 RM	ADT = 30,000 TWLTL	ADT = 30,000 RM	ADT = 40,000 TWLTL	ADT = 40,000 RM	ADT = 50,000 TWLTL	ADT = 50,000 RM
1	30	2	8.94	5.82	8.94	5.82	8.94	5.82	8.94	5.82
		4	9.83	5.82	9.83	5.82	9.83	5.82	9.83	5.82
		6	10.73	5.82	10.73	5.82	10.73	5.82	10.73	5.82
	60	2	6.36	5.82	6.36	5.82	6.36	5.82	6.36	5.82
		4	7.26	5.82	7.26	5.82	7.26	5.82	7.26	5.82
		6	8.15	5.82	8.15	5.82	8.15	5.82	8.15	5.82
2	30	2	12.02	7.78	12.02	7.78	12.02	7.78	12.02	7.78
		4	12.92	7.78	12.92	7.78	12.92	7.78	12.92	7.78
		6	13.82	7.78	13.82	7.78	13.82	7.78	13.82	7.78
	60	2	9.45	7.78	9.45	7.78	9.45	7.78	9.45	7.78
		4	10.34	7.78	10.34	7.78	10.34	7.78	10.34	7.78
		6	11.24	7.78	11.24	7.78	11.24	7.78	11.24	7.78
3	30	2	15.11	9.74	15.11	9.74	15.11	9.74	15.11	9.74
		4	16.01	9.74	16.01	9.74	16.01	9.74	16.01	9.74
		6	16.90	9.74	16.90	9.74	16.90	9.74	16.90	9.74
	60	2	12.53	9.74	12.53	9.74	12.53	9.74	12.53	9.74
		4	13.43	9.74	13.43	9.74	13.43	9.74	13.43	9.74
		6	14.33	9.74	14.33	9.74	14.33	9.74	14.33	9.74

Total Accidents/Mi/Yr Expected: 6 Lane Sections

Signals per mi	Drives per mi	Approach per mi	ADT = 20,000 TWLTL	ADT = 20,000 RM	ADT = 30,000 TWLTL	ADT = 30,000 RM	ADT = 40,000 TWLTL	ADT = 40,000 RM	ADT = 50,000 TWLTL	ADT = 50,000 RM
1	30	2	46.27	16.99	97.11	62.49	147.96	107.99	198.81	153.66
		4	59.23	16.99	110.08	62.49	160.93	107.99	211.77	153.66
		6	72.20	16.99	123.04	62.49	173.89	107.99	224.74	153.66
	60	2	19.41	16.99	70.26	62.49	121.11	107.99	171.96	153.66
		4	32.38	16.99	83.22	62.49	134.07	107.99	184.92	153.66
		6	45.34	16.99	96.19	62.49	147.04	107.99	197.88	153.66
2	30	2	78.64	39.45	129.49	84.95	180.33	130.45	231.18	176.13
		4	91.60	39.45	142.45	84.95	193.30	130.45	244.15	176.13
		6	104.57	39.45	155.42	84.95	206.26	130.45	257.11	176.13
	60	2	51.78	39.45	102.63	84.95	153.48	130.45	204.33	176.13
		4	64.75	39.45	115.60	84.95	166.44	130.45	217.29	176.13
		6	77.71	39.45	128.56	84.95	179.41	130.45	230.26	176.13
3	30	2	111.01	61.92	161.86	107.42	212.71	152.92	263.55	198.60
		4	123.98	61.92	174.82	107.42	225.67	152.92	276.52	198.60
		6	136.94	61.92	187.79	107.42	238.64	152.92	289.48	198.60
	60	2	84.16	61.92	135.00	107.42	185.85	152.92	236.70	198.60
		4	97.12	61.92	147.97	107.42	198.82	152.92	249.66	198.60
		6	110.08	61.92	160.93	107.42	211.78	152.92	262.63	198.60

Total Accidents/MVM Expected: 4 Lane Sections

Signals per mile	Drives per mile	Approach per mile	ADT = 10,000 TWLTL	ADT = 10,000 RM	ADT = 30,000 TWLTL	ADT = 30,000 RM	ADT = 50,000 TWLTL	ADT = 50,000 RM
1	25	2	6.31	4.64	6.31	4.64	6.31	4.64
		4	6.31	4.64	6.31	4.64	6.31	4.64
		6	6.31	4.64	6.31	4.64	6.31	4.64
		8	6.31	4.64	6.31	4.64	6.31	4.64
	50	2	6.31	4.64	6.31	4.64	6.31	4.64
		4	6.31	4.64	6.31	4.64	6.31	4.64
		6	6.31	4.64	6.31	4.64	6.31	4.64
		8	6.31	4.64	6.31	4.64	6.31	4.64
2	25	2	8.60	7.36	8.60	7.36	8.60	7.36
		4	8.60	7.36	8.60	7.36	8.60	7.36
		6	8.60	7.36	8.60	7.36	8.60	7.36
		8	8.60	7.36	8.60	7.36	8.60	7.36
	50	2	8.60	7.36	8.60	7.36	8.60	7.36
		4	8.60	7.36	8.60	7.36	8.60	7.36
		6	8.60	7.36	8.60	7.36	8.60	7.36
		8	8.60	7.36	8.60	7.36	8.60	7.36
3	25	2	10.89	10.08	10.89	10.08	10.89	10.08
		4	10.89	10.08	10.89	10.08	10.89	10.08
		6	10.89	10.08	10.89	10.08	10.89	10.08
		8	10.89	10.08	10.89	10.08	10.89	10.08
	50	2	10.89	10.08	10.89	10.08	10.89	10.08
		4	10.89	10.08	10.89	10.08	10.89	10.08
		6	10.89	10.08	10.89	10.08	10.89	10.08
		8	10.89	10.08	10.89	10.08	10.89	10.08
4	25	2	13.18	12.80	13.18	12.80	13.18	12.80
		4	13.18	12.80	13.18	12.80	13.18	12.80
		6	13.18	12.80	13.18	12.80	13.18	12.80
		8	13.18	12.80	13.18	12.80	13.18	12.80
	50	2	13.18	12.80	13.18	12.80	13.18	12.80
		4	13.18	12.80	13.18	12.80	13.18	12.80
		6	13.18	12.80	13.18	12.80	13.18	12.80
		8	13.18	12.80	13.18	12.80	13.18	12.80

Total Accidents/Mi/Yr Expected: 4 Lane Sections

Signals per mile	Drives per mile	Approach per mile	ADT = 10,000 TWLTL	ADT = 10,000 RM	ADT = 30,000 TWLTL	ADT = 30,000 RM	ADT = 50,000 TWLTL	ADT = 50,000 RM
1	25	2	21.89	20.51	99.44	58.85	177.00	97.19
		4	4.18	20.51	81.73	58.85	159.29	97.19
		6	-13.53	20.51	64.03	58.85	141.58	97.19
		8	-31.24	20.51	46.32	58.85	123.87	97.19
	50	2	21.89	20.51	99.44	58.85	177.00	97.19
		4	4.18	20.51	81.73	58.85	159.29	97.19
		6	-13.53	20.51	64.03	58.85	141.58	97.19
		8	-31.24	20.51	46.32	58.85	123.87	97.19
2	25	2	44.57	36.65	122.13	74.99	199.68	113.33
		4	26.87	36.65	104.42	74.99	181.97	113.33
		6	9.16	36.65	86.71	74.99	164.27	113.33
		8	-8.55	36.65	69.00	74.99	146.56	113.33
	50	2	44.57	36.65	122.13	74.99	199.68	113.33
		4	26.87	36.65	104.42	74.99	181.97	113.33
		6	9.16	36.65	86.71	74.99	164.27	113.33
		8	-8.55	36.65	69.00	74.99	146.56	113.33
3	25	2	67.26	52.79	144.81	91.13	222.37	129.46
		4	49.55	52.79	127.11	91.13	204.66	129.46
		6	31.84	52.79	109.40	91.13	186.95	129.46
		8	14.14	52.79	91.69	91.13	169.24	129.46
	50	2	67.26	52.79	144.81	91.13	222.37	129.46
		4	49.55	52.79	127.11	91.13	204.66	129.46
		6	31.84	52.79	109.40	91.13	186.95	129.46
		8	14.14	52.79	91.69	91.13	169.24	129.46
4	25	2	89.95	68.93	167.50	107.27	245.05	145.60
		4	72.24	68.93	149.79	107.27	227.35	145.60
		6	54.53	68.93	132.08	107.27	209.64	145.60
		8	36.82	68.93	114.38	107.27	191.93	145.60
	50	2	89.95	68.93	167.50	107.27	245.05	145.60
		4	72.24	68.93	149.79	107.27	227.35	145.60
		6	54.53	68.93	132.08	107.27	209.64	145.60
		8	36.82	68.93	114.38	107.27	191.93	145.60

Midblock Accidents/MVM Expected: 6 Lane Sections

Signals per mi	Openings per mile	ADT = 20,000 TWLTL	ADT = 20,000 RM	ADT = 30,000 TWLTL	ADT = 30,000 RM	ADT = 40,000 TWLTL	ADT = 40,000 RM	ADT = 50,000 TWLTL	ADT = 50,000 RM
1	1	2.22	1.92	3.51	1.92	4.80	1.92	6.10	1.92
	2	2.22	1.81	3.51	1.81	4.80	1.81	6.10	1.81
	3	2.22	1.70	3.51	1.70	4.80	1.70	6.10	1.70
	4	2.22	1.59	3.51	1.59	4.80	1.59	6.10	1.59
2	1	2.22	2.08	3.51	2.08	4.80	2.08	6.10	2.08
	2	2.22	1.97	3.51	1.97	4.80	1.97	6.10	1.97
	3	2.22	1.86	3.51	1.86	4.80	1.86	6.10	1.86
	4	2.22	1.75	3.51	1.75	4.80	1.75	6.10	1.75
3	1	2.22	2.25	3.51	2.25	4.80	2.25	6.10	2.25
	2	2.22	2.14	3.51	2.14	4.80	2.14	6.10	2.14
	3	2.22	2.03	3.51	2.03	4.80	2.03	6.10	2.03
	4	2.22	1.92	3.51	1.92	4.80	1.92	6.10	1.92

Midblock Accidents/mi/yr Expected: 6 Lane Sections

Signals per mi	Drives per mile	Approach per mile	ADT = 20,000 TWLTL	ADT = 20,000 RM	ADT = 30,000 TWLTL	ADT = 30,000 RM	ADT = 40,000 TWLTL	ADT = 40,000 RM	ADT = 50,000 TWLTL	ADT = 50,000 RM
1	30	2	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
		4	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
		6	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
	60	2	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
		4	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
		6	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
2	30	2	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
		4	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
		6	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
	60	2	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
		4	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
		6	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
3	30	2	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
		4	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
		6	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
	60	2	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
		4	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17
		6	6.27	11.19	39.84	20.85	73.41	30.51	106.99	40.17

Midblock Accidents/MVM Expected: 4 Lane Sections
Sheet 1: 1 and 2 Signals/mile

Signals per mile	Drives per mile	Approach per mile	ADT = 10,000 TWLTL	ADT = 10,000 RM	ADT = 30,000 TWLTL	ADT = 30,000 RM	ADT = 50,000 TWLTL	ADT = 50,000 RM
1	20	2	3.19	0.86	3.19	0.86	3.19	0.86
		4	1.95	0.86	1.95	0.86	1.95	0.86
		6	0.71	0.86	0.71	0.86	0.71	0.86
		8	-0.53	0.86	-0.53	0.86	-0.53	0.86
	40	2	4.31	-0.06	4.31	-0.06	4.31	-0.06
		4	3.07	-0.06	3.07	-0.06	3.07	-0.06
		6	1.84	-0.06	1.84	-0.06	1.84	-0.06
		8	0.60	-0.06	0.60	-0.06	0.60	-0.06
	60	2	5.44	-0.97	5.44	-0.97	5.44	-0.97
		4	4.20	-0.97	4.20	-0.97	4.20	-0.97
		6	2.96	-0.97	2.96	-0.97	2.96	-0.97
		8	1.72	-0.97	1.72	-0.97	1.72	-0.97
	80	2	6.57	-1.88	6.57	-1.88	6.57	-1.88
		4	5.33	-1.88	5.33	-1.88	5.33	-1.88
		6	4.09	-1.88	4.09	-1.88	4.09	-1.88
		8	2.85	-1.88	2.85	-1.88	2.85	-1.88
2	20	2	3.19	1.64	3.19	1.64	3.19	1.64
		4	1.95	1.64	1.95	1.64	1.95	1.64
		6	0.71	1.64	0.71	1.64	0.71	1.64
		8	-0.53	1.64	-0.53	1.64	-0.53	1.64
	40	2	4.31	0.73	4.31	0.73	4.31	0.73
		4	3.07	0.73	3.07	0.73	3.07	0.73
		6	1.84	0.73	1.84	0.73	1.84	0.73
		8	0.60	0.73	0.60	0.73	0.60	0.73
	60	2	5.44	-0.18	5.44	-0.18	5.44	-0.18
		4	4.20	-0.18	4.20	-0.18	4.20	-0.18
		6	2.96	-0.18	2.96	-0.18	2.96	-0.18
		8	1.72	-0.18	1.72	-0.18	1.72	-0.18
	80	2	6.57	-1.10	6.57	-1.10	6.57	-1.10
		4	5.33	-1.10	5.33	-1.10	5.33	-1.10
		6	4.09	-1.10	4.09	-1.10	4.09	-1.10
		8	2.85	-1.10	2.85	-1.10	2.85	-1.10

Midblock Accidents/MVM Expected: 4 Lane Sections
Sheet 2: 3 and 4 Signals/mile

Signals per mile	Drives per mile	Approach per mile	ADT = 10,000 TWLTL	ADT = 10,000 RM	ADT = 30,000 TWLTL	ADT = 30,000 RM	ADT = 50,000 TWLTL	ADT = 50,000 RM
3	20	2	3.19	2.43	3.19	2.43	3.19	2.43
		4	1.95	2.43	1.95	2.43	1.95	2.43
		6	0.71	2.43	0.71	2.43	0.71	2.43
		8	-0.53	2.43	-0.53	2.43	-0.53	2.43
	40	2	4.31	1.51	4.31	1.51	4.31	1.51
		4	3.07	1.51	3.07	1.51	3.07	1.51
		6	1.84	1.51	1.84	1.51	1.84	1.51
		8	0.60	1.51	0.60	1.51	0.60	1.51
	60	2	5.44	0.60	5.44	0.60	5.44	0.60
		4	4.20	0.60	4.20	0.60	4.20	0.60
		6	2.96	0.60	2.96	0.60	2.96	0.60
		8	1.72	0.60	1.72	0.60	1.72	0.60
	80	2	6.57	-0.31	6.57	-0.31	6.57	-0.31
		4	5.33	-0.31	5.33	-0.31	5.33	-0.31
		6	4.09	-0.31	4.09	-0.31	4.09	-0.31
		8	2.85	-0.31	2.85	-0.31	2.85	-0.31
4	20	2	3.19	3.21	3.19	3.21	3.19	3.21
		4	1.95	3.21	1.95	3.21	1.95	3.21
		6	0.71	3.21	0.71	3.21	0.71	3.21
		8	-0.53	3.21	-0.53	3.21	-0.53	3.21
	40	2	4.31	2.30	4.31	2.30	4.31	2.30
		4	3.07	2.30	3.07	2.30	3.07	2.30
		6	1.84	2.30	1.84	2.30	1.84	2.30
		8	0.60	2.30	0.60	2.30	0.60	2.30
	60	2	5.44	1.39	5.44	1.39	5.44	1.39
		4	4.20	1.39	4.20	1.39	4.20	1.39
		6	2.96	1.39	2.96	1.39	2.96	1.39
		8	1.72	1.39	1.72	1.39	1.72	1.39
	80	2	6.57	0.47	6.57	0.47	6.57	0.47
		4	5.33	0.47	5.33	0.47	5.33	0.47
		6	4.09	0.47	4.09	0.47	4.09	0.47
		8	2.85	0.47	2.85	0.47	2.85	0.47

Midblock Accidents/Mi/Yr Expected: 4 Lane Sections
Sheet 1: 1 and 2 Signals/mile

Signals per mile	Drives per mile	Approach per mile	ADT = 10,000 TWLTL	ADT = 10,000 RM	ADT = 30,000 TWLTL	ADT = 30,000 RM	ADT = 50,000 TWLTL	ADT = 50,000 RM
1	20	2	13.41	-6.45	45.83	14.27	78.25	34.99
		4	-4.08	-6.45	28.34	14.27	60.76	34.99
		6	-21.58	-6.45	10.84	14.27	43.26	34.99
		8	-39.07	-6.45	-6.65	14.27	25.77	34.99
	40	2	23.91	-6.45	56.33	14.27	88.75	34.99
		4	6.42	-6.45	38.84	14.27	71.26	34.99
		6	-11.07	-6.45	21.35	14.27	53.77	34.99
		8	-28.57	-6.45	3.85	14.27	36.27	34.99
	60	2	34.41	-6.45	66.83	14.27	99.25	34.99
		4	16.92	-6.45	49.34	14.27	81.76	34.99
		6	-0.57	-6.45	31.85	14.27	64.27	34.99
		8	-18.07	-6.45	14.35	14.27	46.77	34.99
	80	2	44.92	-6.45	77.34	14.27	109.76	34.99
		4	27.42	-6.45	59.84	14.27	92.26	34.99
		6	9.93	-6.45	42.35	14.27	74.77	34.99
		8	-7.56	-6.45	24.86	14.27	57.28	34.99
2	20	2	13.41	-3.93	45.83	16.79	78.25	37.51
		4	-4.08	-3.93	28.34	16.79	60.76	37.51
		6	-21.58	-3.93	10.84	16.79	43.26	37.51
		8	-39.07	-3.93	-6.65	16.79	25.77	37.51
	40	2	23.91	-3.93	56.33	16.79	88.75	37.51
		4	6.42	-3.93	38.84	16.79	71.26	37.51
		6	-11.07	-3.93	21.35	16.79	53.77	37.51
		8	-28.57	-3.93	3.85	16.79	36.27	37.51
	60	2	34.41	-3.93	66.83	16.79	99.25	37.51
		4	16.92	-3.93	49.34	16.79	81.76	37.51
		6	-0.57	-3.93	31.85	16.79	64.27	37.51
		8	-18.07	-3.93	14.35	16.79	46.77	37.51
	80	2	44.92	-3.93	77.34	16.79	109.76	37.51
		4	27.42	-3.93	59.84	16.79	92.26	37.51
		6	9.93	-3.93	42.35	16.79	74.77	37.51
		8	-7.56	-3.93	24.86	16.79	57.28	37.51

Midblock Accidents/Mi/Yr Expected: 4 Lane Sections
Sheet 2: 3 and 4 Signals/mile

Signals	Drives	Approach	ADT = 10,000		ADT = 30,000		ADT = 50,000	
per mile	per mile	per mile	TWLTL	RM	TWLTL	RM	TWLTL	RM
3	20	2	13.41	-1.41	45.83	19.31	78.25	40.03
		4	-4.08	-1.41	28.34	19.31	60.76	40.03
		6	-21.58	-1.41	10.84	19.31	43.26	40.03
		8	-39.07	-1.41	-6.65	19.31	25.77	40.03
	40	2	23.91	-1.41	56.33	19.31	88.75	40.03
		4	6.42	-1.41	38.84	19.31	71.26	40.03
		6	-11.07	-1.41	21.35	19.31	53.77	40.03
		8	-28.57	-1.41	3.85	19.31	36.27	40.03
	60	2	34.41	-1.41	66.83	19.31	99.25	40.03
		4	16.92	-1.41	49.34	19.31	81.76	40.03
		6	-0.57	-1.41	31.85	19.31	64.27	40.03
		8	-18.07	-1.41	14.35	19.31	46.77	40.03
	80	2	44.92	-1.41	77.34	19.31	109.76	40.03
		4	27.42	-1.41	59.84	19.31	92.26	40.03
		6	9.93	-1.41	42.35	19.31	74.77	40.03
		8	-7.56	-1.41	24.86	19.31	57.28	40.03
4	20	2	13.41	1.11	45.83	21.83	78.25	42.55
		4	-4.08	1.11	28.34	21.83	60.76	42.55
		6	-21.58	1.11	10.84	21.83	43.26	42.55
		8	-39.07	1.11	-6.65	21.83	25.77	42.55
	40	2	23.91	1.11	56.33	21.83	88.75	42.55
		4	6.42	1.11	38.84	21.83	71.26	42.55
		6	-11.07	1.11	21.35	21.83	53.77	42.55
		8	-28.57	1.11	3.85	21.83	36.27	42.55
	60	2	34.41	1.11	66.83	21.83	99.25	42.55
		4	16.92	1.11	49.34	21.83	81.76	42.55
		6	-0.57	1.11	31.85	21.83	64.27	42.55
		8	-18.07	1.11	14.35	21.83	46.77	42.55
	80	2	44.92	1.11	77.34	21.83	109.76	42.55
		4	27.42	1.11	59.84	21.83	92.26	42.55
		6	9.93	1.11	42.35	21.83	74.77	42.55
		8	-7.56	1.11	24.86	21.83	57.28	42.55